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Localization of a Speech Target in Nondirectional and Directional Noise as a Function of Sensation Level

by Kim S. Abouchacra and Tomasz Letowski

ARL-TR-6030 **June 2012**

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14. ABSTRACT
Both the detectability and localizability of a target signal must be considered when the signal is presented with multiple other sounds in an environment. When target and noise sources are separated spatially, target speech detection, recognition, and intelligibility improve substantially. Less information is known, however, about the effect of spatial separation on a listener's localization performance. In the present study, we examine the accuracy of localization judgments in various multiple sound source environments. Localization performance was examined as a function of sensation level (SL) in an attempt to account for changes in signal audibility resulting from changes in directional position of the sound source. A target speech signal (S) was presented at 0-, 6-, 12-, and 18-dB SL in reference to hearing threshold masked by 65-dB A-weighted nondirectional (NDN) or directional (DN) speech-spectrum noise. The listeners consisted of 40 young adults with normal hearing. At the beginning of the study, directional detection thresholds (DDTs) were established for all listeners in each target-noise condition (5 NDN conditions and 35 DN conditions). We calculated the appropriate SLs needed for the localization task from the DDTs of individual listeners. All listeners demonstrated decreases in localization error (°) and increases in localization precision (%) as SL increased. Changes in overall localization performance as a function of SL were similar in NDN and DN. When target-noise conditions were grouped according to the location of S, localization performance was (a) most accurate when S originated from 0° and +90° azimuth, (b) relatively accurate when S was positioned at +45° azimuth, and (c) poor when S originated from rear-horizontal plane positions (+135° and 180° azimuth). At lower SLs, localization performance was poorer than performance reported in other studies of localization in noise. This report covers localization biases, error types, and the relationship between target detection and localization.

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1. Introduction

Human listeners operate in auditory environments rich with sounds that are constantly interacting with one another. Some of these sounds may be important and meaningful to a listener, whereas other sounds may be distracting and have little value. Sounds in the environment that carry meaningful information or convey a message to the listener may be considered target signals. Target signals can arise from a single location or from multiple locations in the environment and may compete for the listener's attention at any one moment. All other sounds in the environment may be considered distracters (noise) that can influence or degrade a listener's ability to perceive target signals. If distracters develop from many sources and the listener perceives the distracters as "all surrounding" and producing a fused image, they can be classified as nondirectional noise (NDN). On the other hand, if distracter sounds arise from identifiable locations in the environment, the distracters can be classified as directional noise (DN).

Both NDN and DN noises have been shown to affect target signal detection, recognition, and speech intelligibility (e.g., Abouchacra et al., 1998a; 1998b; Dirks and Wilson, 1969; Good et al., 1997; Hirsh, 1950; Lorenzi et al., 1999; Saberi et al., 1991; Thompson and Webster, 1964). Specifically, previous findings suggest that as differences between the target signal and noise become less distinct, the target signal is less perceptible and its location more uncertain. Difficulty in discriminating between the target and noise can be minimized if the target signal and noise are distinctly different in composition, if the target level is substantially higher than the noise level, and if a spatial separation exists between a target and noise source. If these conditions are present, target signal detection, recognition, and speech intelligibility are relatively accurate in noise-filled environments, with a great deal of contribution to good performance arising from spatial hearing cues that are accurately received and used by the listener.

A listener who correctly processes and interprets spatial hearing cues can perform quite effectively in an acoustic environment (Blauert, 1983; Middlebrooks and Green, 1991). One set of spatial hearing cues that a listener uses to interpret the auditory environment is interaural difference cues. Interaural difference cues are perceived binaurally, and they include differences in level, phase, and arrival time of sound reaching the two ears. Interaural level differences are important for localizing sounds that have high-frequency energy (e.g., Mills, 1972; Sandel et al., 1955), and interaural phase and arrival time differences help a listener to discern spatial information about sounds with low-frequency energy (e.g., Stevens and Newman, 1936; Wallach et al., 1949). Another set of spatial cues is spectral cues. These cues are processed monaurally and originate from spectral changes in sound resulting from multiple reflections produced as sound impinges on the head, torso, and especially from the convolutions of the pinna. Spectral cues produce a complex pattern of spatial information that is particularly helpful when one is trying to differentiate between front-back or up-down locations (e.g., Batteau, 1967; Butler, 1975; Butler et al., 1990). If interaural difference cues and spectral cues produce ambiguous information, voluntary or involuntary head movements can assist the listener in resolving these ambiguities, because during head movements, the listener may receive many "cue samples" of the acoustic environment that can help clarify confusing spatial information (Pollack and Rose, 1967; Thurlow and Runge, 1967; Wallach, 1940). In acoustically degraded environments (e.g., environments containing substantial amounts of noise or reverberation), however, these cues may be compromised, resulting in inaccurate resolution of auditory space.

The effect of noise on spatial perception of target signals has been studied consistently for many years. Specifically, many studies have examined the effect of DN (e.g., speech spectrum, white, pink, narrow band noise) on speech detection, recognition, and intelligibility thresholds, and on detection thresholds of nonspeech signals (e.g., Abouchacra et al., 1998; Bronkhorst, 1990; Carhart et al.,1969; Dirks and Wilson, 1969; Good et al., 1997; Hirsh, 1950; Kock, 1950; Saberi et al., 1991). Regardless of signal and noise type, results indicate that thresholds of target signals in noise improve as the separation between the target and DN source increases. Specifically, when target and noise sources are coincident (control condition), detection thresholds are the poorest among measurements. However, when sources are separated and originate from locations on different sides of the listener's mid-saggital plane, target signal thresholds improve by as much as 16 to 20 dB (e.g., Good et al., 1997; Saberi et al., 1991). Observed improvement in target thresholds in noise for other combinations of target-noise source locations vary from 1 to 15 dB compared to the control condition. These directional changes have been subsequently used to predict the listener's detection of signal in noise in anechoic spaces (e.g., Zurek, 1983). However, less is known about directional thresholds for targets in NDN (Abouchacra and Letowski, 2004; Braasch and Hartung, 2002). Abouchacra and Letowski (2004) measured directional thresholds for speech targets presented in NDN and DN. With the exception of a target signal presented from 180° azimuth, results of this study revealed that detection thresholds for speech in NDN were relatively uniform, varying only ±2 dB across all but one target location. When speech originated from 180° azimuth, the target was most difficult to detect, and thresholds differed from thresholds measured at other target locations by 3 to 4 dB.

A limited amount of data exists on how the presence of additional sound sources (e.g., DN or NDN) affects the perceived location of a target signal. The available literature consistently reveals that significant levels of background noise can seriously degrade both localization accuracy (LA) and precision (Braasch and Hartung, 2002; Good and Gilkey, 1996; Lorenzi et al., 1999). In acoustic environments containing DN, localization performance is inferior when targets originate from rear locations, with respect to the listener, than from locations in the frontal-horizontal plane. Similar findings have been reported for speech and nonspeech targets presented in NDN (Abouchacra et al., 1998a; 1998b; Dobbins and Kindick, 1966; 1967).

Results of the previously cited studies suggest that detectability of a target signal should be considered in localization measurement, especially when multiple sounds are present in an acoustic environment. Detectability of a target varies across azimuth position because of changes in spatial hearing cues and changes in masking by noise sources (Good et al., 1997). Although it seems reasonable to expect that localization performance will be high in conditions where targets are spatially separated from noise and when the signal is clearly audible above the noise, unequivocal evidence confirming this assumption is not available in the literature. Existing research has shown that target-noise conditions favoring signal detection (i.e., conditions where the target is most easily detected in noise) do not always produce the highest localization performance (Good et al., 1997; Lorenzi et al., 1999). Similar findings have been reported in studies of lateralization, where conditions favoring signal detection resulted in poor lateralization (e.g., Cohen, 1981).

The focus of the present study was to examine systematically a listener's ability to locate the source of a speech signal in the presence of NDN or DN, with the speech presented at four sensation levels (SLs) and separated from the noise source by varying amounts. SL refers to the decibel level of a target signal above its masked detection threshold in a given target-noise arrangement. A target signal presented at 6-dB SL, for example, indicates that the target is 6 dB above a listener's established masked directional detection threshold (DDT) for a specific target-noise source configuration. The SL approach to defining target-noise conditions attempts to consider both the influences of audibility and changes in a listener's spatial hearing cues on localization judgments in environments containing multiple sound sources.

In previous studies of sound localization in noise, signal-to-noise ratio (SNR) has been used to describe sound levels in the test environment. SNR has been defined as the intensity of the signal relative to the level of the noise in reference to (a) a single location in the environment with the listener absent or (b) a single target-noise condition with the listener present in the environment. When the first definition of SNR is used, a +6-dB SNR, for example, simply indicates that the target level is 6 dB higher than the noise level relative to a reference location in the test environment (e.g., Lorenzi et al., 1999). When SNR is calculated according to the second definition, a listener's detection threshold in noise is measured first for a specific reference condition (e.g., target = 0° azimuth, noise = 0° azimuth). This detection threshold defines 0-dB SNR. Manipulations of the signal (or noise) above and below 0-dB SNR (e.g., –6 dB, +6-dB SNR) at the reference condition determines other SNRs, which are applied to both the reference condition and other target-noise configurations (e.g., Good and Gilkey, 1996). When the SNR method is used to define target-noise environments in localization experiments, the effect of changes in spatial hearing cues on localization judgments will be reflected in listener responses. However, the SNR approach, with its reference to a single reference location/position, does not attempt to control for additional changes in audibility that result when target-noise sources are moved to locations other than the reference location/condition (i.e., the approach cannot account for the effects of spatial separation on target audibility). While some researchers have addressed the relationship between target audibility (detectability) and LA by converting SNR to estimated SL values, to the authors' knowledge, the present study is the first to consider the effect of audibility on localization performance by measuring individualized DDTs at all tested target-noise conditions prior to measuring localization judgments. The specific research questions asked were (1) how does localization performance change as a function of audibility (sensation level) and target-noise configuration and (2) what types of errors and biases in localization judgments occur in acoustic environments containing moderate-level noise?

2. Method

2.1 Test Participants

Forty listeners (20 male and 20 female), ages 18 to 29 years (mean age = 21.4; SD [standard deviation] = 3.4), were recruited from a local community college and paid $10/h to participate in the study. Each listener underwent a thorough audiological evaluation that revealed the following:

- No recent history of otologic pathology.
- Air-conduction thresholds better than 15-dB HL from 0.25 to 8 kHz in octave steps (ANSI, 1989).
- Hearing symmetry at each test frequency (i.e., interaural threshold differences at each test frequency were $\leq$5 dB).
- Normal tympanograms.
- Confirmed acoustic reflexes on contralateral stimulation.
- Masking level differences (MLD) >6 dB for a 500-Hz tone presented in narrow-band noise (Olsen et al., 1976).[*]

The Edinburgh Handedness Inventory (Oldfield, 1971) revealed that 37 listeners were right-handed, two listeners were left-handed, and one listener was ambidextrous. All listeners were native speakers of English, and none had participated in psychoacoustic experiments previously.

2.2 Stimuli

A single spondaic word, *northwest*, from the Central Institute for the Deaf (CID) W-1 standardized word lists, was selected as the target signal (figure 1). This word was selected because the two syllables have been shown to be the most homogeneous, with respect to audibility, across eight investigations evaluating uniformity of CID W-1 standardized

[*]The MLD was included because it identifies listeners with processing problems in a frequency region that is important for speech detection in noise (Dirks and Wilson, 1969).

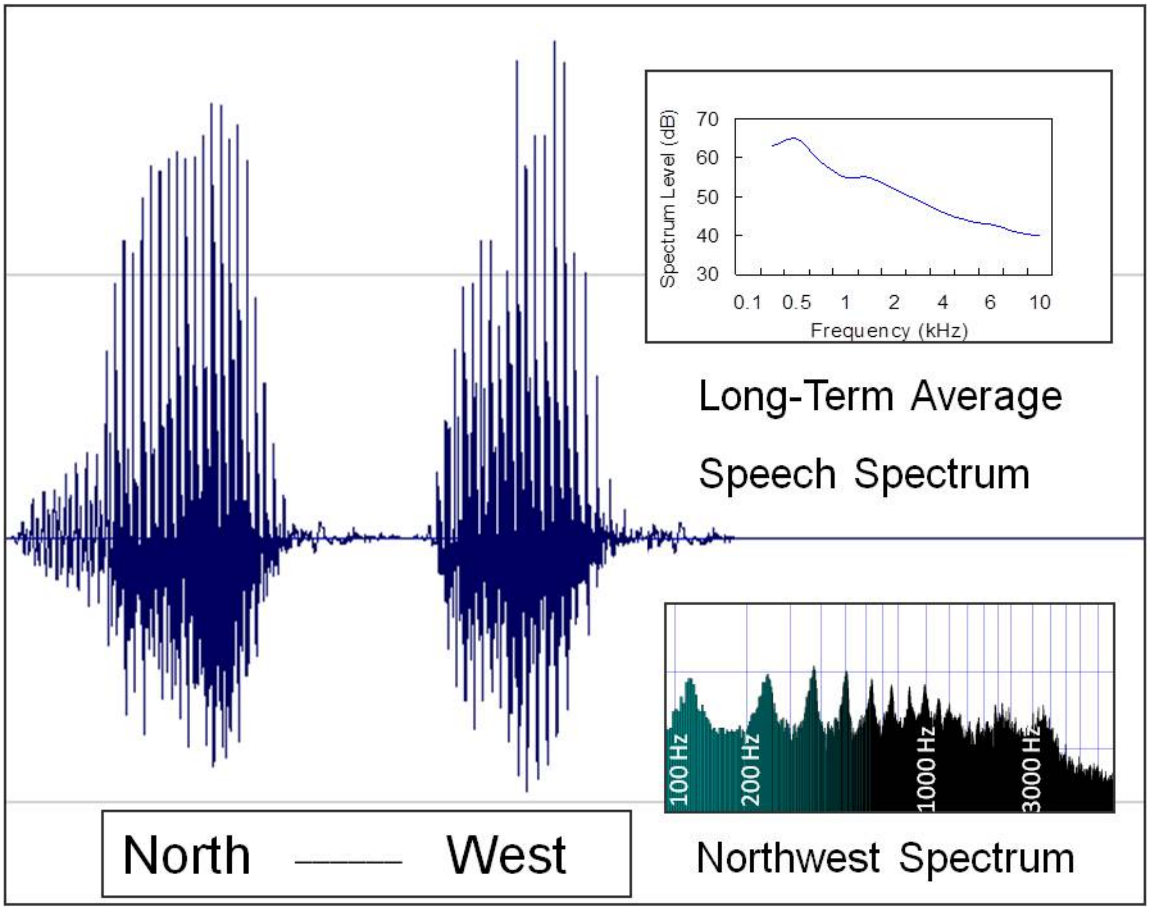

Figure 1. Temporal and spectral characteristics of the target signal (northwest*)* and the long-term average spectrum of speech spectrum noise (SSN).

words (Olsen and Matkin, 1991). Additionally, Abouchacra et al. (1998b) reported that homogenous spondaic words, such as the word *northwest*, are robust test signals for spatial tasks performed in noise because they minimize inter- and intra-listener variability. During testing, the target signal was generated on a personal computer (PC), and a programmable attenuator was used to control the presentation level of the target signal.

A broadband noise shaped to a frequency spectrum approximating the long-term average speech spectrum (ANSI, 1992) was used for both the NDN and DN test conditions (figure 1). The noise spectrum was limited to 0.2 to 10 kHz. Throughout the experiment, the speech spectrum noise was set to a constant level of 65 dB A-weighted when measured at the listener's head position (listener absent). This level represents noise levels that occur in typical listening environments and approximates the noise level permitting satisfactory voice communication (95% accuracy) at a 1-m distance (EPA, 1974). The noise level also falls within a range where speech thresholds are determined mainly by SNR (i.e., levels $\geq$55 dB A), with very little contribution from the absolute noise level (Duquesnoy and Plomp, 1983; Ebata et al., 1968; Rao and Letowski, 2003). That is, in noise levels at or above 55 dB A-weighted, absolute detection thresholds and the effect of spatial separation on thresholds are stable. At lower noise levels (i.e., $\leq$50 dB SPL), detection thresholds are more variable, and the effect of spatial separation on detection threshold is significantly smaller (Ebata et al., 1968).

2.3 Apparatus

Stimuli were presented via six loudspeakers (Bose 108515K) that were housed in a 2.7- × 2.7- × 1.9-m anechoic chamber (IAC, Microdyne Series; V = 18.7 m^3) meeting free-field test conditions for frequencies above 170 Hz. Noise was presented through either (1) four matched loudspeakers distributed in space to create NDN or (2) a single boom-mounted loudspeaker (N) acting as a DN source. The target signal was presented through a second boom-mounted loudspeaker acting as a directional speech signal (S). As shown in figure 2, the two booms were suspended from the ceiling of the chamber and pivoted on the same axis, holding the loudspeakers at a uniform 1 m from the listener's head at ear level (1.3 m from the floor of the chamber). Each of the boom-mounted loudspeakers could be independently rotated to any azimuth location, in 1° azimuth steps, using computer-controlled stepper motors (Arrick Robotics). Although they could be positioned at any location along the horizontal plane, the boom-mounted loudspeakers were restricted to positions of 0°, $\pm$45°, $\pm$90°, $\pm$135°, and 180° azimuth during testing. Such an arrangement allowed for 64 specific combinations of S and N locations to be used in the study. However, to make the study more manageable, only 35 combinations were used after excluding symmetrical combinations (e.g., $S_{90}N_{135}$ was used while $S_{-90}N_{-135}$ was not).

Forty different target-noise conditions were used in this study: 5 conditions involved presentation of S in NDN and 35 conditions involved presentation of S in DN (table 1). When a test condition required S and DN to be presented at the same azimuth position, S and DN waveforms were added with an analog mixer, routed to the same channel of an amplifier, and then the S+DN stimulus was directed to one of the two boom-mounted loudspeakers.

The loudspeaker system was calibrated at the beginning of each test day throughout data collection. A 75-dB A-weighted pink noise was presented sequentially through each of the six loudspeakers used in the study. Output levels from all loudspeakers were compared and adjusted to be equal (within $\pm$2 dB) at one-third-octave band intervals from 0.2 through 10 kHz. Measurements of the output from the four loudspeakers used to create NDN revealed that a diffuse sound field, matching ANSI S12.6-1988 (ANSI, 1988), was present within a 25-cm sphere (12.5-cm radius) around the listener's head position (listener absent). The sound pressure level variability of the NDN sound field was within 3 dB as determined by moving and rotating the test microphone within the test area. To evaluate whether the room acoustics had an effect on signals presented through the boom-mounted loudspeakers, outputs from the loudspeakers were measured at each of the eight test positions. For each boom-mounted loudspeaker and test position, sound levels measured in the center of the room (B&K 4134 microphone; listener

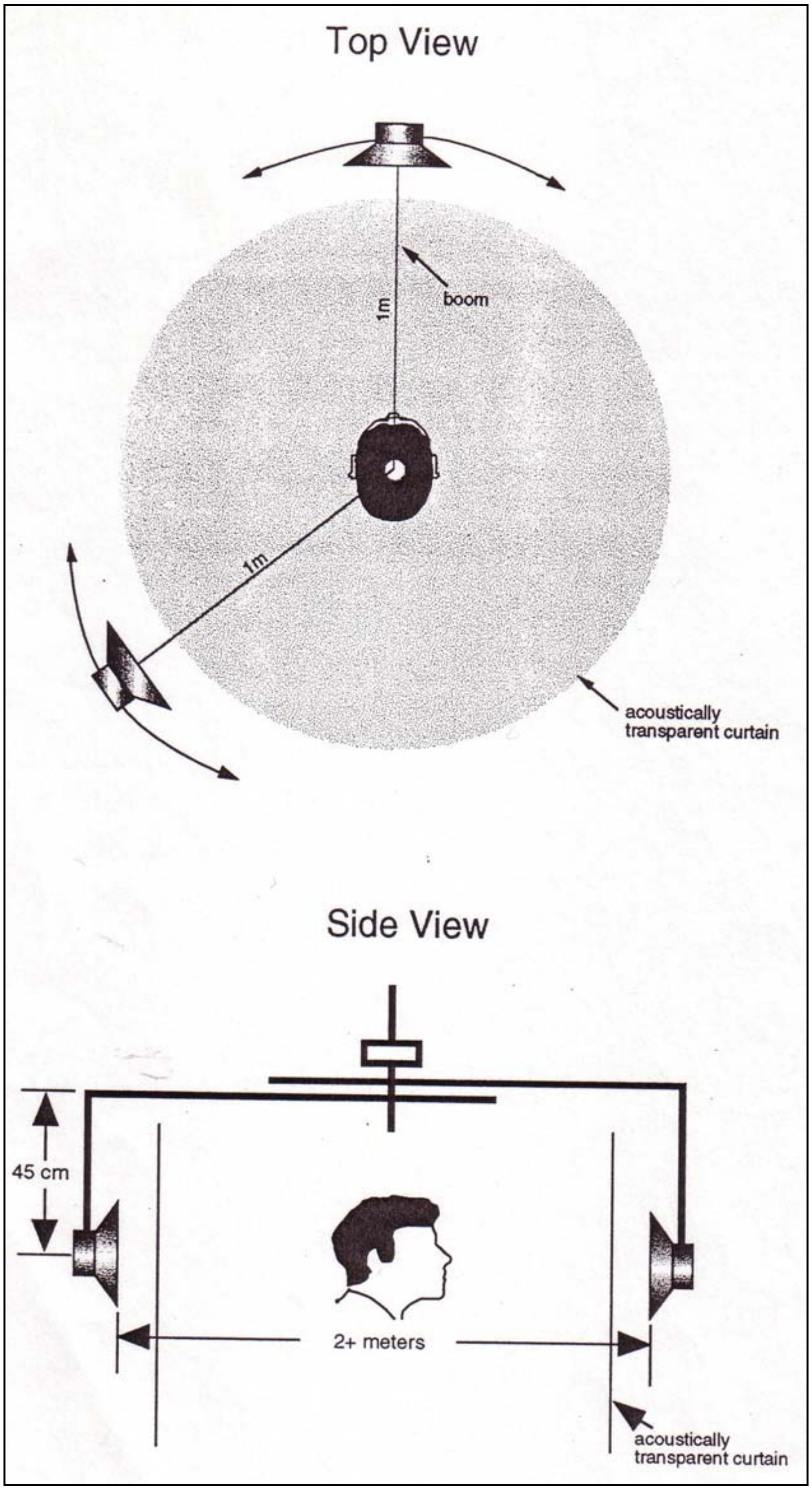

Figure 2. View of the boom loudspeaker system used to present the signal and directional noise.

Table 1. Target signal (S) and noise (N) source conditions, as represented by S-location and N-location, respectively.

Target-Noise Condition	S-location /N-location	Target-Noise Condition	S-location /N-location
1	S_0 N_0	21	S_{-90} N_{135}
2	S_0 N_{-45}	22	S_{-90} N_0
3	S_0 S_{-90}	23	S_{-135} N_0
4	S_0 N_{-135}	24	S_{-135} N_{-45}
5	S_0 N_{180}	25	S_{135} N_{90}
6	S_{45} S_0	26	S_{135} N_{135}
7	S_{-45} N_{-45}	27	S_{135} N_{180}
8	S_{45} N_{90}	28	S_{-135} N_{135}
9	S_{-45} N_{-135}	29	S_{135} N_{-90}
10	S_{45} N_{180}	30	S_{-135} N_{45}
11	S_{-45} N_{135}	31	S_{180} N_0
12	S_{45} N_{-90}	32	S_{180} N_{45}
13	S_{-45} N_{45}	33	S_{180} N_{-90}
14	S_{90} N_0	34	S_{180} N_{135}
15	S_{-90} N_{-45}	35	S_{180} N_{180}
16	S_{-90} N_{-90}	36	S_0 N_{NDN}
17	S_{-90} N_{-135}	37	S_{-45} N_{NDN}
18	S_{90} N_{180}	38	S_{90} N_{NDN}
19	S_{-90} N_{135}	39	S_{-135} N_{NDN}
20	S_{90} N_{-90}	40	S_{180} N_{NDN}

Note: The numbers following the letters S and N represent the azimuth location (°) of the target signal and direction noise, respectively. (0° is the location directly in front of the listener, and 180° is the location directly behind the listener; –90° is the location directly to the listener's left side, and +90° is the location directly to the listener's right side.)

absent) varied <1 dB between loudspeakers at any of the 11 one-third-octave bands. Additionally, outputs from the boom-mounted loudspeakers were assessed with a KEMAR (Knowles Electronic Manikin for Acoustic Research) manikin seated at the listener's intended position during testing to evaluate the influence of the human head on sounds (Burkhard, 1978). As each boom-mounted loudspeaker was rotated sequentially through the eight test positions, a computer-generated chirp signal (SYSid Software, Ariel Corp.) was presented, and responses were measured with two B&K 4134 microphones positioned at KEMAR's left and right ear. When a boom-mounted loudspeaker presented a signal from 0° azimuth, left- and right-ear sound pressure level differences were <1 dB. Changes measured in left and right microphone responses for other azimuth locations, because of the presence of KEMAR, were in agreement with data reported by Shaw (1974).

During the study, the listener was seated in the center of the anechoic chamber on a custom-built, height-adjustable chair that was bolted to the floor. Chamber lights remained off during testing to prevent the listener from seeing the loudspeaker locations. Additionally, a dark, acoustically transparent curtain (inside diameter = 1.75 m) was used to block the six loudspeakers and overhead boom apparatus from the listener's view. A white LED, located within the cylindrical curtain directly in front of the listener (slightly below eye level), was the only source used to illuminate the listener's surroundings. This LED was on continuously throughout the experiment. A second green LED, located immediately below the white LED, was used to mark test trials.

Head movements were restricted during testing; however, no restraints were used to keep the listener's head from moving. Instead, two plumb bobs were dropped from the roof of the curtain and positioned 50 cm apart directly in front of the listener. The listener was asked to align the plumb bobs visually during test trials. A custom-made neck support, which had two small contact points that touched the left and right side of the upper neck, was used to help listeners maintain a constant head position; a slight turn of the head resulted in a feeling of increased pressure at the left or right contact point, depending on the direction of head movement. Finally, a head-tracking electromagnetic device (Polhemus, 3-Space Isotrak) mounted to the back of the listener's head using a Velcro strap monitored head orientation. Any responses made by listeners during excessive head movement ($\geq$3° azimuth) were discarded, and the test trial was repeated.

Listeners made localization judgments via a touch-sensitive response board (KoalaPad) and stylus. The response board template displayed a drawing of the listener's head in the listening environment, a pointer ring for indicating localization responses, and a small black square to indicate that nothing was heard during a trial (figure 3). Every position on the board had unique x and y values assigned to it. Touching the board with the stylus resulted in a pair of signals representing x and y coordinates. These coordinates were sent to the PC via a smart port. At the computer, the pairs of x and y values for any position on the pointer ring could be transformed into locations within the horizontal plane (in degrees azimuth). Precision of sensing was within $\pm$1° azimuth.

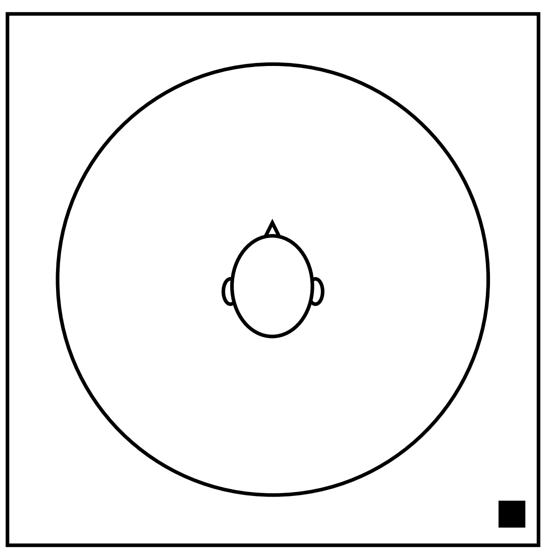

Figure 3. Template displayed on the touch-sensitive response board.

All responses indicated by the listener were recorded in the listener's response file. The file also contained information about the identity of the target-noise condition (a number from 1 to 40), the listener's masked DDT measured for the condition (in dB SPL), the sensation level of the target signal (in dB SL), the type of noise (NDN or DN), the source location of the target (in degrees azimuth), and the source location of the noise (in degrees azimuth) if DN was present. These data were subsequently used to calculate localization error patterns.

2.4 Procedure

This study required listeners to determine the location of target signals presented in noise. The target signal (S) was presented in the 5 NDN and 35 DN conditions listed in table 1. For all conditions, noise was held constant at a level of 65 dB A-weighted, while the level of S was presented at four sensation levels: 0-, 6-, 12-, and 18-dB SL.

To establish appropriate sensation levels for S in the various target-noise conditions, masked DDTs for each listener were measured. A standard Bekesy tracking procedure was used to measure the 40 DDTs for each listener (Bekesy, 1947).* The listener tracked the level of S in each condition using a hand-held response button. S was presented initially at a level about 20 dB below an estimated DDT level for a given target-noise condition (as determined during a pilot study). During each trial, the signal level increased in intensity until the listener heard the signal and pressed and held the response button. The listener continued pressing the button, causing the signal to gradually decline until it was no longer heard and the listener released the button. With this tracking procedure, the intensity of the target signal continued to increase and decrease via listener control at a rate of 5 dB/s over a period of 60 s after the first press of the button (i.e., after first reversal in the listener response). The DDT was defined as the mean midpoint of all excursions (signal level changes) over the 60-s period.

After the 40 DDTs were measured for a given listener, the PC calculated individualized SLs for the listener in each target-noise condition. The measured DDT for a given target-noise condition (DDT_i) was defined as 0-dB SL. Likewise, 6-dB SL was defined as DDT_i + 6 dB, 12-dB SL equaled DDT_i + 12 dB, and 18-dB SL was equivalent to DDT_i + 18 dB. Individualized SLs were used when the listener's localization performance was tested in the 40 target-noise conditions.

During localization testing, noise was present in the environment at all times, with NDN or DN present during test trials, and NDN present between trials to mask the noise caused by the boom loudspeakers being moved into new positions for the next trial. This part of the study involved a 30-min training session and two, 2-h test sessions (test and retest session) separated by no more than 2 days. In each session, we measured the LA (+/–15° azimuth range) of targets presented in DN and NDN. During testing, the listener was instructed to clip or pull back his or her hair to allow unimpeded exposure of the ears. The experimenter positioned the listener on the height-

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*Research comparing Bekesy tracking with other adaptive threshold procedures indicates that Bekesy tracking yields repeatable thresholds in a shorter period of time and with greater listener confidence (Abouchacra et al., 1996).

adjustable chair so that the center of the listener's head (interaural axis) corresponded with the center of the test environment, and the listener's ears were aligned with the centers of the boom-mounted loudspeakers. The experimenter then secured the head tracker on the listener's head and instructed the listener to rest the back of his or her neck on the neck support and to align the plumb bobs visually. The listener received tape-recorded instructions on how to use the touch-sensitive response board, which was mounted to the arm of the chair and positioned in front of the listener at chest level. Without head movement, the listener could easily view the entire response board by shifting visual gaze downward. The listener was told that the sound could originate from any azimuth position along a single horizontal plane (0° elevation); therefore, localization judgments could be made anywhere on the pointer ring* using a stylus. In other words, the precision of a listener's responses was not restricted even though localization measures were only evaluated along the horizontal plane at eight azimuth locations. Following these instructions, each listener received 30 min of training on the localization task to get familiar and comfortable with the test procedure and response mode. During training, S was always presented at 18 dB SL, and the listener was given verbal feedback about the correct position of the target signal when responses were incorrect. Only listeners achieving 95%–100% LA by the end of the training session were included as test participants.

Following training, formal localization testing began. In a test and retest session, performance was evaluated in the 40 target-noise conditions with S presented at four sensation levels: 0-, 6-, 12-, and 18-dB SL. The order of presentation was randomized across sensation levels and noise environments in each session. No feedback about the correctness of responses was given. During a localization trial, DN or NDN was turned on, and the green LED on the light display flashed several times. The flashing light informed the listener that a trial will soon begin and allowed the listener time to check his or her head position (i.e., to check that the plumb bobs were aligned and his or her neck was resting against the neck support). When the light stopped flashing and remained illuminated, the listener was required to listen for S. After a delay of random length (0.5–3 s), S (~1 s) was presented. The listening period ended when the green LED turned off. At this point, the response board became active and awaited a response from the listener. After the PC recorded the listener's localization response, the boom-mounted loudspeakers moved into position for the next trial. The PC kept a complete record of the listener response history for localization judgments across test sessions. A total of 320 responses were recorded for each listener (2 sessions × 4 sensation levels × 40 target-noise environments).

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*Smith-Abouchacra (1993) found that LA was within ±3° azimuth of the true loudspeaker location using this method for recording responses in a quiet environment.

3. Results and Discussion

3.1 Detection

3.1.1 Directional Detection Thresholds

Mean DDTs measured in 65-dB A-weighted noise varied from 43.0- to 55.1-dB SPL across all 40 target-noise conditions. The related SDs varied from 2.5 to 4.4 dB. Mean DDTs were subjected to a repeated-measures analysis of variance (ANOVA-R), with loudspeaker configuration (target-noise condition) as the within-subjects factor. Results of the ANOVA-R revealed a statistically significant difference in DDTs across target-noise condition ($F [39, 599] = 24.94$, $p < 0.001$). A Schéffè post hoc multiple comparison test, using appropriate error terms that were adjusted for sphericity (Huynh-Feldt adjustment), revealed several homogeneous subsets, with members of a given subset not statistically different from each other ($p > 0.05$). One subset (Subset A) included the five conditions where S was most easily detected (mean DDTs = 43.0- to 44.2-dB SPL; SDs = 2.6–3.8 dB). The five target-noise conditions in this subset, $S_{45}N_{-135}$, $S_{45}N_{-45}$, $S_{90}N_{-135}$, $S_{135}N_{-135}$, and S_0N_{-135}, involved DN and could be characterized as having a large separation between the S and DN sources ($\geq$90°), with the target located in the frontal-horizontal plane for all but one condition ($S_{135}N_{-135}$) and sources located on opposite sides of the midsaggital plane (with the exception of S_0N_{-135}). Another subset (Subset D) included the five conditions producing poorest DDTs (mean DDTs = 54.6- to 55.1-dB SPL; SDs = 2.7–3.5 dB). All target-noise conditions in Subset D involved DN that was coincident with the position of S: S_0N_0, $S_{-45}N_{-45}$, $S_{-90}N_{-90}$, $S_{135}N_{135}$, and $S_{180}N_{180}$.

Mean DDTs for the remaining 25 target-DN conditions fell between these two extremes and could be reasonably divided into two further subsets described by the amount of spatial separation existing between the target and noise sources. The first subset (Subset B) included 15 DN conditions with mean DDTs ranging from 45.0- to 48.4-dB SPL (SDs = 2.5–3.8 dB). Eleven of the 15 conditions had a separation of >135° azimuth between the target and noise source, two conditions had a 90° separation, and two conditions had a 45° separation between sources. The other subset (Subset C) included 10 DN conditions with mean DDTs ranging from 49.0- to 53.0-dB SPL (SDs = 2.7–4.4 dB). Eight of the 10 conditions had a spatial separation of 45° azimuth between the target and noise source; the two remaining conditions involved S and DN originating from the midsaggital plane (S0N180 and S180N0). Mean DDTs measured for all NDN conditions fell within Subset B (mean DDTs of 45.0- to 47.0-dB SPL; SDs of 3.3–3.6 dB), with the exception of condition S180NNDN (mean DDT = 50-dB SPL; SD = 3.6 dB), which was included in Subset C.

These results suggest that for targets presented in DN, detectability changes considerably across target-noise arrangements, with average changes in signal audibility varying by as much as

12 dB. In general, DDTs improved as the amount of spatial separation increased between the signal and noise source. Results are comparable to other studies measuring DDTs for speech and nonspeech signals in DN. Abouchacra et al. (1996; 1998b) found detectability changes of 13–15 dB for spondaic words presented in directional speech spectrum noise and multitalker noise. Large changes in DDTs, as large as 16–20 dB, have been reported by Saberi et al. (1991) and Good et al. (1997) for target-noise conditions involving nonspeech targets in DN. Similar changes in detectability (i.e., >15 dB) have been reported in MLD studies (see Durlach and Colburn [1978] for a review). For more complex speech tasks tested in real and simulated free fields, such as speech recognition or intelligibility, smaller changes in DDTs (<8 dB) have been reported and depend on the target-noise configuration (e.g., Dirks and Wilson, 1969; Hirsh, 1950; Ricard and Miers, 1994). The poorest detectability when target signals and directional noise sources are coincident has been reported consistently for broadband signals and speech (e.g., Abouchacra et al., 1998b; Saberi et al., 1991; Suzuki and Sone, 1986); however, this is not always true when tones are presented in noise (e.g., Santon, 1987). In most cases, though, it appears that changes in audibility across target-noise conditions can be significant and have the potential to influence a listener's localization performance, especially near threshold.

Unlike the large changes in DDTs found across conditions involving DN, results of the present study suggest that detection thresholds in NDN were relatively uniform (within 2 dB of each other), with the exception of $S_{180}N_{NDN}$. For the $S_{180}N_{NDN}$ condition, the target is slightly more difficult to detect. Thus, spatial location of speech targets in NDN does not appear to have as great an influence on DDTs as spatial location of targets in DN.

3.1.2 Percentage of Detected Targets at 0-dB SL

Recall that the mean midpoint of all excursions measured during Bekesy tracking was used to define DDT_i, and that the level of the target signal at DDT_i was defined as 0-dB SL for each target-noise condition in the localization experiment. After the experiment was completed, the data were examined to determine what was actually audible at 0-dB SL during the localization task. Listeners' responses were reviewed for "unheard" signals (i.e., as indicated by a response in the black square on the response board). The percentage of unheard responses was subtracted from 100% to establish the total percentage of responses that was heard at 0-dB SL for each target-noise condition. Results of this examination revealed that detection of S at 0-dB SL ranged from 84% (268/320 trials) to 89% (285/320 trials) across DN conditions for each listener.

In NDN, 84% of targets (268/320 trials) were detected when S was presented at 0-dB SL. A similar calculation was made for S presentations at 6-, 12-, and 18-dB SL. All presentations of S (i.e., 100% or 320/320 trials) were heard at these higher sensation levels across the 40 target-noise conditions. Although the percentage of audible signals at 0-dB SL across conditions was not truly at detection threshold (i.e., at 50% detection), the measured percentage of signals detected was relatively uniform across listeners and considered comparable across DN and NDN conditions during the localization task.

3.2 Localization

3.2.1 Qualitative and Descriptive Summaries of Localization Performance

Localization responses collected for each target-noise condition and SL were compared across the test and retest session. Histograms revealed that localization responses were not normally distributed in all target-noise conditions or SLs. As a result, raw test and retest data were analyzed using the Wilcoxon Matched Pairs Test, which is a nonparametric alternative to t-tests for dependent samples. No statistically significant differences were found between test and retest data for any target-noise condition or SL ($p > 0.05$). Accordingly, test and retest data were collapsed across the session for subsequent descriptive and statistical analyses.

Localization responses obtained from listeners across all listening conditions, or groups of conditions, are summarized in table 2 and figure 4. The table describes the size of localization error as a function of SL, and the figure describes LA (percent correct); however, prior to discussing these data, the raw data will be examined first. Raw data for the localization task are shown on polar plots included in appendix A, and a descriptive summary of these responses is presented in tabular format in appendix B. Because the polar plots and descriptive summary table represent an intermediate step in creating the graphs shown in figure 4 and the data presented in table 2, they will be explained first.

Table 2. Localization error as a function of SL, averaged across all signal conditions or specific S-anchored conditions for both NDN and DN competing noise. All table values are reported in degrees azimuth.

Target-Noise Condition	**Sensation Level**				
	18-dB SL	**12-dB SL**	**6-dB SL**	**0-dB SL**	**Average**
All Conditions					
NDN	33.8	45.1	48.5	55.9	46.1
DN	36.4	40.7	38.8	41.0	39.2
S-Anchor					
S_0					
NDN	0.2	0.1	0.4	3.5	4.2
DN	0.5	1.7	11.1	8.6	5.5
S_{45}					
NDN	10.0	10.1	4.3	22.1	11.6
DN	3.3	11.3	15.9	14.0	11.1
S_{90}					
NDN	0.9	1.5	3.2	26.0	7.9
DN	1.4	1.8	4.3	13.2	5.2
S_{135}					
NDN	47.0	34.8	59.9	49.7	47.9
DN	34.2	36.1	46.2	56.9	43.4
S_{180}					
NDN	111.0	178.8	179.6	178.0	161.9
DN	142.8	117.1	126.2	132.6	129.7

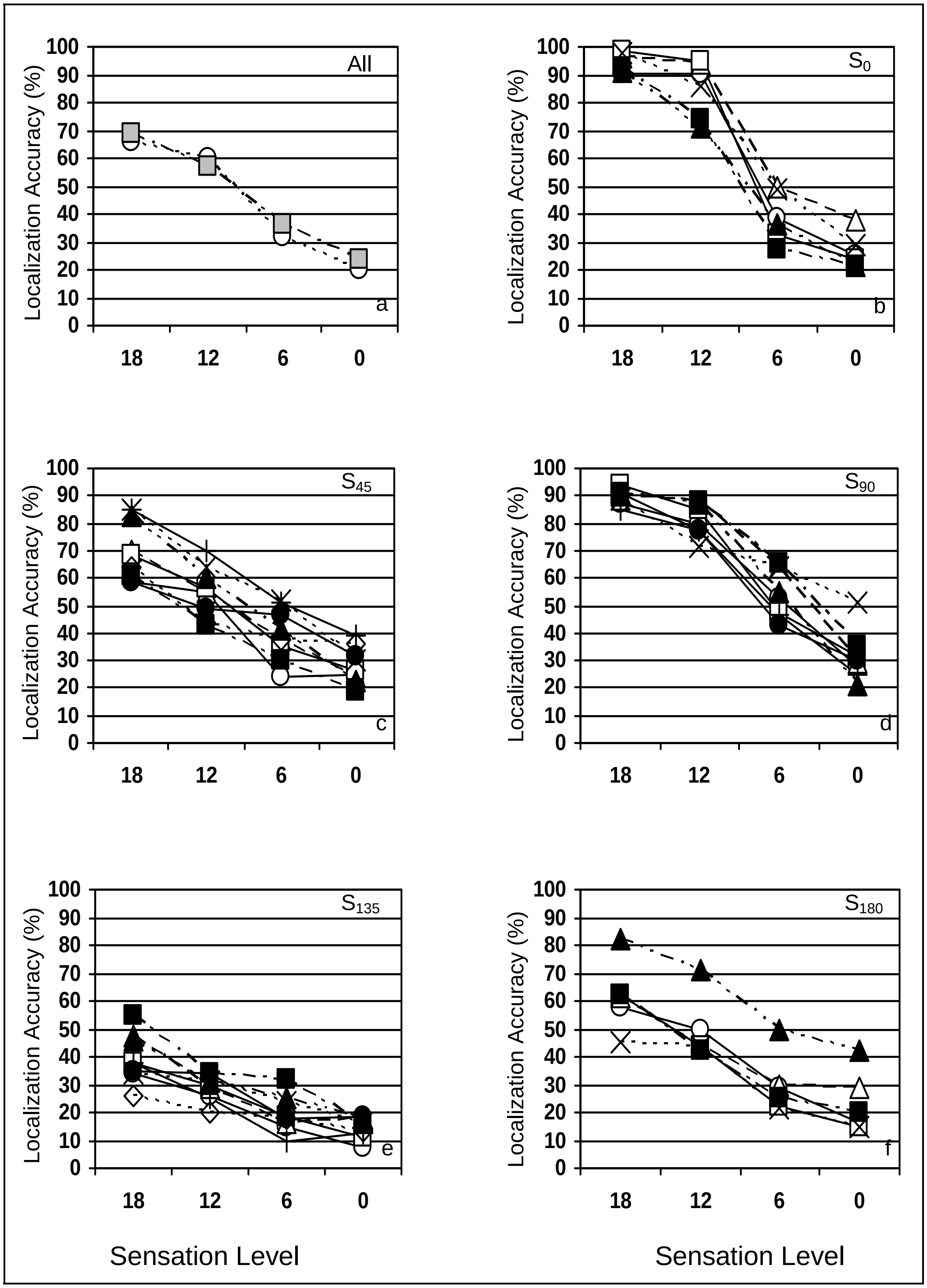

Figure 4. LA as a function of sensation level (SL in dB): (a) overall LA averaged across all NDN (open circle) and DN (shaded square) conditions; (b–f) LA as a function of SL when S (or mirror image) is positioned at 0°, 45°, 90°, 135°, and 180° azimuth.

Note: symbols for the noise position in panels b–f are as follows: N_0 = open triangle, N_{45} = open square, N_{90} = X symbol, N_{135} = solid square, N_{180} = solid triangle, N_{-135} = solid circle, N_{-90} = + symbol, N_{-45} = open diamond, and N_{NDN} = open circle.

Each column (panel) of polar plots in appendix A represents a single target-noise condition, which can be identified by the number in the upper left-hand corner of a panel. Each panel includes four polar plots showing the data for sensation levels of 0-, 6-, 12-, and 18-dB SL on the bottom, lower-mid, upper-mid, and top panel, respectively. The azimuth location of the target and noise source in DN conditions (i.e., panels 1–35) are represented by the letters S and N, respectively, and placed at the appropriate location on each polar plot. For conditions involving S presented in NDN (i.e., panels 36–40), only the location of S is denoted on the polar plots. The first, second, and third ring on each polar plot represent 10, 20, and 30 localization responses, respectively. Overall, the polar plots revealed a systematic improvement in localization performance for all target-noise conditions, as SL increases from 0 to 18 dB.

Polar plots summarizing localization responses collected with S at 0° azimuth in DN at various locations (i.e., conditions 1–5) are displayed in the first five panels of appendix A. For these conditions, localization performance was extremely accurate at 12- and 18-dB SL. At lower SLs, adjacent (ADJ) errors (i.e., responses to the left or right of the true S location) and front-back (FB) errors (i.e., responses made around 180° azimuth) were present.

When S originated from ±45° azimuth in DN (panels 6–13), fairly accurate localization performance was seen at 18-dB SL. LA was good at 12-dB SL for some of the target-noise conditions in this subset (i.e., panels 8, 10, 12, and 13). At lower SLs, however, both ADJ and FB errors (i.e., responses made in the rear-horizontal plane at locations other than 180°) were present. Another notable error made by many listeners when S was located at ±45° azimuth was a response between ±75° and ±90° azimuth (e.g., panels 6, 7, 9, and 12).

For target-noise conditions involving S presented at ±90° azimuth in DN (panels 14–22), LA was high at 12- and 18-dB SL. However, response precision (i.e., compactness of responses around the true S location) was slightly poorer than responses recorded when S was presented at 0° azimuth in DN (i.e., panels 1–5). At 6-dB SL, LA for S presentations at ±90° remained high for most target-noise conditions (panels 15, 16, 17, 18, 21, and 22). For other conditions in this subset at 6-dB SL, ADJ errors were present.

Poor localization performance was found for all conditions at 0-dB SL, with the exception of the condition in which S and DN were coincident at –90° azimuth (panel 16).

Polar plots summarizing localization responses collected during target-noise conditions involving S at ±135° azimuth in DN (panels 23–30) revealed poor performance at all SLs, with the following exception. Good localization performance was obtained at 18-dB SL when S and N were coincident at 135° azimuth (panel 26). For this subset of target-noise conditions, a significant number of ADJ errors and/or back-front (BF) errors (i.e., responses made in the frontal-horizontal plane at locations other than near 0° azimuth) were present at all SLs. An additional finding for this subset of conditions was that at lower SLs, many localization judgments were made at ±90° azimuth.

When S originated from 180° azimuth in DN (panels 31–35), summary polar plots revealed three general findings. First, a significant number of BF errors (i.e., responses made near 0° azimuth) were present in all conditions; however, the fewest number of BF errors were found for condition 35, in which S and DN occupied the same spatial position at 180° azimuth. Second, if BF errors are ignored, localization responses were extremely precise, clustering within a narrow range around 180° azimuth at 12- and 18-dB SL. Third, when S and DN were coincident at 180° azimuth, LA remained relatively high across all SLs; for the other target-noise conditions in this subset, ADJ errors were present in addition to the abundant number of BF errors at lower SLs.

Localization responses to S presented in NDN are presented in panels 36–40 of appendix A. In general, response accuracy and localization error types occurring for each S location in NDN were similar to those found for corresponding S locations in DN. That is, localization responses measured in NDN were most precise when S was located at 0° azimuth (panel 36). When S was located at –45° azimuth (panel 37), few FB errors were made. Instead, a large number of ADJ errors were present, with an especially large number of responses reported at ~75° azimuth across SLs. When S originated from 90° azimuth (panel 38), LA was good at all SLs except 0-dB SL. When S was located at –135° azimuth (panel 39), a significant number of BF and ADJ errors were present at all SLs. Finally, when S was presented at 180° azimuth in NDN (panel 40), the distribution of responses was bimodal, with responses evenly divided between 180° and 0° azimuth.

Appendix B presents a descriptive summary of the raw localization responses. The 40 target-noise conditions are listed in the first column of the table. Because collected responses in each target-noise condition and SL were not normally distributed (i.e., skewed distributions, variable amounts of kurtosis, or multimodal distributions were present), median values (Med) were used as a measure of distribution central tendency. As a measure of data variability, interquartile range (IQR) was used; IQR represents 50% of the data centering on a median value, and it is derived from the 25th (Q_1) and 75th (Q_3) quartile values (i.e., IQR = Q_3-Q_1). These values (Q_1, Med, Q_3, and Q_3-Q_1) are presented for each condition and SL. Additionally, signed localization error (LE_s), which is defined as the azimuth difference and direction between perceived and true S location, is presented for each target-noise condition and SL.

3.2.2 Anchoring of Localization Data

To enable patterns of localization performance shown in appendices A and B to be seen more readily in table 2 and figure 4, target-noise conditions were anchored (grouped) as follows. First, conditions were grouped as a function of five S locations: 0°, 45°, 90°, 135°, or 180° azimuth (positive azimuth positions). To anchor the conditions in this manner, all target-noise conditions involving S at –45°, –90°, or –135° azimuth were converted to their “mirror image” positive azimuth locations while maintaining the originally designed spatial separation between a signal and noise source. For example, to anchor at S_{45}, all conditions involving S_{-45} were converted to positive positions while keeping the appropriate spatial separation between the target and noise;

thus, $S_{-45}N_{-45}$ (condition 7), $S_{-45}N_{-135}$ (condition 9), $S_{-45}N_{135}$ (condition 11), and $S_{-45}N_{45}$ (condition 13) were converted to $S_{45}N_{45}$, $S_{45}N_{135}$, $S_{45}N_{-135}$, and $S_{45}N_{-45}$, respectively. This type of conversion was also conducted for the NDN condition, such that $S_{-45}N_{NDN}$ (condition 37) was converted to $S_{45}N_{NDN.}$ After conversion, these data were combined with the originally designed positive S_{45} conditions (i.e., $S_{45}N_0$, $S_{45}N_{90}$, $S_{45}N_{180}$, and $S_{45}N_{-90}$) and presented together as a group (e.g., figure 4, panel c).*

3.2.3 Localization Accuracy as a Function of Sensation Level

LA was examined for all target-noise conditions, with LA defined as the percentage of responses within a cut-off range of ±15° azimuth of the true target location. Using the procedure described in the previous section, we made mirror-image conversions for some target-noise conditions to create S-anchored groups. These data are presented in figure 4. As expected, localization performance deteriorated as SL decreased. When overall LA in DN and NDN were compared as a function of SL (panel *a*), little difference in LA was found between noise types. Specifically, for both DN and NDN, LA ranged from 66% to 69% at 18-dB SL, 57%–60% at 12-dB SL, 32%–36% at 6-dB SL, and 20%–24% at 0-dB SL.

When S was anchored at 0°, 45°, 90°, 135°, and 180° azimuth (panels b–f, respectively), the slope of degradation varied across S-anchored positions and depended on the signal location, noise location, and angular separation between the two. For S_0 (panel b) and S_{90} (panel d) anchored conditions, LA was high at 18 dB (85%–98%) and relatively high at 12-dB SL (70% –95%). As SL decreased to lower sensation levels, however, a significant drop in LA was seen between 12- and 6-dB SL for S_0 anchored conditions, with little further reduction in LA between 6- and 0-dB SL. On the other hand, a more gradual decrease in performance occurred for S_{90} conditions as SL decreased from 12- to 6-dB SL and from 6- to 0-dB SL. Note, however, that LA at 0-dB SL for $S_{90}N_{90}$ was significantly higher than LA measured in other noise positions of this subset (panel d).

Poorer LA was found for the remaining S-anchored groups. For S_{45} conditions (panel c), LA decreased at a rate of about 15% for each 6-dB SL decrease, with LA ranging from 60% to 85% at 18-dB SL to 20%–39% at 0-dB SL across noise positions. Of all the S-anchored groups, the poorest LA occurred for S_{135} conditions (panel e), with LA ranging from 26% to 55% at 18-dB SL to 8%–19% at 0-dB SL, which amounted to about an 8% decrease in performance for each drop in SL. In general, LA measured for S_{180} conditions (panel f) was better than LA measured in S_{135} conditions but slightly poorer than average performance measured in S_{45} anchored conditions. With the exception of condition $S_{180}N_{180}$, LA ranged from 45% to 64% at 18-dB SL to 15%–29% at 0-dB SL across noise positions. However, performance for condition $S_{180}N_{180}$ was significantly higher across SLs compared to other noise locations in this subset of target-noise conditions, with LA findings mimicking performance measured in S_{90} anchored conditions.

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*Using the same environment and testing conditions, Abouchacra et al. (1996; 1998b) found the test environment to be acoustically similar, yielding symmetrical directional detection responses from listeners for “mirror image” locations.

3.2.4 Localization Error as a Function of Sensation Level

Absolute values of median localization error (LE)—that is, median unsigned error, defined as the median azimuth difference between the perceived and true S location, regardless of error direction—are presented as a function of SL in table 2. These values were derived from the signed error values (LE_s) in appendix B. Overall LE at each SL, averaged across target presentations in NDN (five conditions) and DN (35 conditions), is summarized in the first two rows of the table, respectively. As SL decreased from 18- to 0-dB SL, median LE increased from about 34° to 56° for NDN conditions (i.e., 22° increase in LE), whereas LE remained relatively stable at about 36° to 41° across SL in DN (i.e., 5° increase in LE). Differences in LE between noise types were greatest at lower SLs (i.e., a difference of 10.7° at 6-dB SL and 14.9° at 0-dB SL), with larger LEs recorded for conditions that included NDN.

LEs were subsequently examined while the position of the target signal was anchored. Comparisons of median LEs revealed that for both noise types, median errors averaged across SLs (last column of table) were generally small (4°–8°) when S originated from front (0°) and side (90°) locations. For target-noise conditions anchored at S_{45}, slightly larger errors (11°) were observed for both noise types. The largest LEs were found when S originated from rear locations (i.e., S_{135} and S_{180} anchored conditions), with median LEs averaging 43°–48° for S_{135} anchored conditions and 130°–162° for S_{180} conditions in NDN and DN. Large errors in localization judgments for targets originating at rear locations resulted predominately from the sizable number of BF errors made by listeners (see appendix A, panels 24–35 for DN and 39–40 for NDN).

3.2.5 Discussion of Localization Accuracy and Error as a Function of SL

When LA and precision are examined together as a function of SL, results of the present study suggest that spatial performance is best when S originates directly in front of or to the side of a listener. This finding supports results of studies of localization performance in quiet environments where it has been shown repeatedly that sound sources in the frontal hemisphere are localized more accurately than sound sources in the rear hemisphere (Blauert, 1983; Butler et al., 1990; Hofman and Van Opstal, 1998; Middlebrooks and Green, 1991; Mills, 1972; Oldfield and Parker, 1984; Stevens and Newman, 1936). Results of the current study indicate the poorest localization precision for targets originating from rear locations (135° and 180° azimuth). In quiet, localization errors for targets originating from 180° azimuth are larger than errors for targets presented from 0° azimuth. A similar finding was noted in the current study for targets presented in NDN and DN. For lateral target locations (i.e., positions moving away from the midsaggital plane toward ±90° azimuth), other researchers have reported smaller localization errors for target signals originating from front hemisphere locations (e.g., ±45° azimuth) compared to rear locations (e.g., ±135° azimuth) in quiet (Carlile et al., 1997; Makous and Middlebrooks, 1990; Oldfield and Parker, 1984; Wightman and Kistler, 1989b). Similar conclusions have been reached in this study as well as in other studies measuring relative localization[*] performance (Jacobsen, 1976; King and Laird, 1930; Scharf and Canevet, 1980) and absolute localization[†] performance in DN or NDN (Dobbins and Kindick, 1966; 1967; Good et al., 1997; Lorenzi et al., 1999; Mershon and Lin, 1987). While the patterns of performance found in the present study are comparable to patterns of localization performance in quiet environments, measured LA and LE did not achieve the high performance levels reported for quiet environments across all test conditions.

In the present study, LA increased (LE decreased) as the target signal became more audible. To achieve reasonably good localization performance (i.e., $\geq$80% LA with median LE $\leq$10°), the results of this study suggest that 12- to 18-dB SL is needed when S originates from front (0°) and side locations ($\pm$90°), and 18-dB SL is needed for three target-noise conditions in the S_{45} anchored group (i.e., $S_{45}N_{90}$, $S_{45}N_{180}$, $S_{45}N_{-90}$). Similar levels of localization precision were not attainable at 18-dB SL for the remaining six S_{45} anchored conditions, all nine S_{135} anchored conditions, and five of the six S_{180} anchored conditions. These results support the notion that signal-to-noise conditions needed for highly accurate localization of targets from all positions in an acoustic environment may need to be much better than the levels used in this experiment (Abouchacra et al., 1998a; Hirsh, 1950). However, it may be the case that optimal localization performance may not be achievable in noise across all target-noise conditions (even at higher sensation levels) without the aid of training, feedback, or free head movement. Finally, it is noteworthy that in some of the target-noise conditions where S and DN were spatially coincident (e.g., $S_{90}N_{90}$ and $S_{180}N_{180}$), higher than expected LA was noted at lower SLs. This finding may be the result of an accurate perception of S at lower SLs or a bias in responses toward the clearly audible DN when listeners heard a signal but were unsure of its location (see section 3.4 for further discussion).

Some studies have reported accurate localization in DN at levels very close to a listener's detection threshold. For example, Good and Gilkey (1996) assessed localization performance as a function of nine SNRs calculated from the individual subject's detection threshold for a single target-noise condition (S_0N_0). To estimate performance as a function of SL for the other target-noise conditions, the authors adjusted the data by using mean detection thresholds measured in the various target-noise environments from a previous study. The SNR-to-SL converted data revealed that localization performance was similar to performance measured in quiet environments at SLs $\geq$4 dB in the left-right dimension and at SLs $\geq$8 dB in the front-back dimension when DN was fixed at 0° azimuth, and the location of the target signal was varied. Other researchers have reported similar findings of good localization performance near threshold for targets presented in DN (e.g., Good et al., 1997; Lorenzi et al., 1999). Highly accurate localization performance near a listener's detection threshold was not found in the present study

[*]Relative localization typically involves a discrimination task measuring the smallest detectable angle difference between a target and a reference sound (e.g., minimal audible angle [MAA]).

[†]Absolute localization typically involves an identification task requiring the listener to indicate which of several possible source positions was active.

across similar target-noise conditions. Differences in the findings between studies may be the result of variations in the way in which signal and noise levels were defined and the criteria used for determining accuracy of localization judgments.

3.3 Comparison of Target Detection and Localization Performance

The relationship between target detection and localization in noise is complex. One view of the relationship is that if the target signal is clearly audible in noise, the target location can be identified as being different from the location of the noise. As a result, attention can be focused on the target, and the target source should be localizable (e.g., Cherry, 1953). Another view of the relationship between target detection and localization is that audibility is not enough for accurate target localization; instead, both audibility and resolution of spatial hearing cues (i.e., interaural difference cues, spectral cues or both) are needed before a target source can be localized accurately (e.g., Good et al., 1997).

Previous research has shown that target-noise conditions favoring signal detection (i.e., conditions where S is most easily detected in noise) do not always produce the highest localization performance (Good et al., 1997; Lorenzi et al., 1999). Similar findings have been reported in studies of lateralization, where conditions favoring signal detection resulted in poor lateralization (e.g., Cohen, 1981). In the present study, audibility of the target signal in noise was addressed by examining localization performance as a function of sensation level. In all 40 target-noise conditions, the target was clearly audible in the 65-dB A-weighted noise, especially at 12- and 18-dB SL. If accurate localization depends solely on signal audibility, then accurate localization of a target signal should not be significantly affected by noise at high sensation levels. In the present study, the five target-noise conditions in which S was most easily detected in noise (i.e., lowest DDTs) were $S_{-45}N_{135}$, $S_{-45}N_{45}$, $S_{-90}N_{135}$, $S_{-135}N_{135}$, and S_0N_{-135}. Of these conditions, localization performance was high (>80% LA and median LE <10°) for $S_{-90}N_{135}$ and S_0N_{-135} at 18-dB SL only. Of the five target-noise conditions in which S was most difficult to detect in noise (i.e., those conditions in which S and DN were coincident), localization performance was only high for S_0N_0, $S_{-90}N_{-90}$, and $S_{180}N_{180}$ at 18-dB SL and for S_0N_0 at 12-dB SL. The good localization performance measured in these three conditions may have occurred because listeners actually heard and reported the true target location or because they reported a spatial position where *any* sound was heard (i.e., the location of the target or noise source). These findings suggest that audibility of a target signal in noise is not enough for accurate localization performance. Instead, it appears that both audibility and binaural signal processing of both the target and the masking sources may be affecting listeners' localization judgments.

One reason why audibility may not be sufficient for accurate localization judgments is that listeners "perceive" portions of the noise to be a part of the target signal at lower sensation levels, and therefore the true location of the target signal becomes "blurred." Another reason may be that audibility is not necessarily "hearing the entire target signal." That is, the target may be clearly audible because some of its components are robust, but other components of the target signal necessary for clarifying its spatial location (most likely high frequencies) are lacking. In a study by Myers et al. (1996) examining the level difference between detection and recognition thresholds for filtered sound effects, it was found that increases in target level above detection thresholds of as large as 20 dB were sometimes necessary before the target could be accurately recognized. A similar phenomenon may be occurring when localizing target signals. A third reason why audibility may not be enough for good localization performance may result from the use of unfamiliar target signals. When listeners have limited exposure to a particular target signal, they may require higher sensation levels before achieving localization performance levels matching localization ability measured for familiar sounds or matching performance of other listeners who have extensive experience with the signal. Finally, if head movements are restricted, listeners may not be able to resolve various "cones of confusion"* at levels near target audibility, especially when targets are unexpected or unfamiliar.

The results of the present study suggest that localization performance reached a high and stable level by 18-dB SL when S originated from 0° and 90° azimuth, regardless of the amount of spatial separation between sources. For all other S-anchored groups, localization performance did not achieve plateau by 18-dB SL, and higher SLs are needed for unequivocal spatial performance. Interestingly, one of the criteria for entry into the study was the achievement of ≥95% LA at 18-dB SL during the training session. All listeners achieved this level of performance by the end of training when feedback was provided. Thus, it appears that listeners' were able to "learn" the unique spectral information for specific locations and correct errors in perceived location with training and immediate feedback. In other words, high levels of localization performance for some target-noise conditions may only be reached with the aid of listener training and feedback and/or free head movements that help a listener resolve ambiguous cue information.

3.4 Error Types and Biases in Localization Judgments

3.4.1 Left-Right (LR) and Right-Left (RL) Errors

LR/RL errors occur when a listener records a localization judgment at a location on the opposite hemisphere of the true target location (re: the midsaggital plane). To determine the frequency of such errors by listeners in the present study, LR/RL errors were examined across all localization responses to targets presented at +45°, +90°, and +135° azimuth. LR/RL errors averaged 1% at 18 dB, 2% at 12-dB SL, 5% at 6-dB SL, and 8% at 0-dB SL across target-noise conditions involving S at +45°, +90°, and +135° azimuth. Thus, as expected, listeners had good LR/RL localization performance even at low sensation levels. Previous studies consistently reported LR/RL errors as infrequent in both noise-filled and noise-free environments (e.g., Abel and Hay,

*Any given point in space is only one member of a locus of points that have the same interaural cue characteristics in terms of time, intensity, and phase differences. The "cone of confusion" refers to members of such a group. Many cones of confusion exist; however, points of confusion can be disambiguated by pinnae cues.

1996; Blauert, 1983; Good and Gilkey, 1996; Makous and Middlebrooks, 1990; Oldfield and Parker, 1984).

3.4.2 Front-Back (FB) and Back-Front (BF) Errors

Langendijk et al. (2001) defined FB/BF errors as “responses that are in the hemifield (front or rear) opposite the target.” An analysis of FB/BF errors defined in this way revealed that BF errors were more common than FB errors for most S locations and listeners in the present study. Averaged across SL, FB errors occurred for 5%–15% of responses when S was at 0° or +45° azimuth. When S was at +135° or 180° azimuth, 15%–40% of responses were BF errors. Both types of errors had tendencies to decrease with increases in SL. The finding that BF errors are more common than FB errors agrees with our previous informal observations for the type of experimental environment used in this study. Many studies in the literature, however, report a prevalence of FB errors over BF errors. Some authors have hypothesized that this is due to the fact that when a listener hears but cannot see a sound-producing object, the listener tends to select sound source locations in the rear hemisphere (Blauert, 1983). This behavior, however, may be limited to situations when the listeners actually see that there is no sound-producing object in front of them.

In the literature, the incidence of FB/BF errors varies considerably and is related, among others, to the presence of noise and/or reverberation, the type of listening environment (real or simulated), and the type and composition of target signal. In the absence of noise, the incidence of FB/BF errors for listeners seated in an anechoic chamber ranges from 2% to 20% (Burger, 1958; Langendijk et al., 2001; Makous and Middlebrooks, 1990; Oldfield and Parker, 1984; Wenzel et al., 1993; Wightman and Kistler, 1989a). In simulated free-field environments, under quiet conditions, FB/BF error rates varied from 15% to as high as 35% for nonindividualized head-related transfer functions (HRTFs)[*] and from 11%–19% for individualized (custom) HRTFs (Begault and Wenzel, 1993; Besing and Koehnke, 1995; Ricard and Meirs, 1994; Wenzel et al., 1993; Wightman and Kistler, 1989a). When high-frequency energy is removed from a target signal, the rate of FB/BF errors has been shown to increase in quiet environments (Bronkhorst, 1995; Wightman and Kistler, 1997).

When directional noise is present in the environment, FB/BF errors are reportedly larger than in noise-free environments. Ricard and Meirs (1994) found an overall error rate of 18% when studying LA in DN at 0° azimuth, in a simulated free-field environment using nonindividualized HRTFs. Abouchacra et al. (1998b) reported FB/BF errors of 16%–32% for S and NDN presented in a sound-treated booth, with the percentage of FB/BF errors depending on the specific location of the target source and SNR. In the present study, the percentage of FB/BF errors ranged from 5% to 40% and was dependent on the target-noise environment and SL.

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[*]Head-related transfer functions (HRTFs) refer to filtering algorithms applied to input signals that simulate spatial hearing cues. When this processed (filtered) sound is presented through earphones, the listener experiences spatialized sound. When “generic” filters are used as HRTFs, resolution of auditory space is poorer than when “individualized” HRTFs are used.

These data suggest that noise can mask or alter the necessary spatial hearing cues for accurate localization.

3.4.3 Directional Biases

The data and discussion presented in the previous section indicate that the presence of noise in the environment has an influence on localization judgments of a target source. Bulter and Nauton (1964) reported a "pushing" of a listener's response away from the noise source or a "pulling" of the response toward the noise. Others have reported that listeners' judgments are closer to the noise source location when the target level is close to threshold. These influences are referred to here as directional biases. Similar to the reports by other researchers, directional biases were present in the data, even at high sensation levels. When target signals were presented at ±45° or ±135° azimuth, listeners made more lateral errors (toward ±90°) than medial errors (toward 0° or 180°) for DN located at 0°, 180°, or ±90° azimuth. This result indicates that listeners had a tendency to hear the sound source more lateralized than it actually was. We refer to this phenomenon as a lateral bias. When S originated from ±90° azimuth, listeners had a tendency to respond more frontally (toward 0^o) regardless of the noise type, DN location, and SL (considered here as a medial bias). Contrary to our findings showing the presence of lateral biases when speech was presented at ±45° or ±135° azimuth, Sandel et al. (1955) showed biases toward the midsaggital plane (0° or 180° azimuth) when 2- and 3-kHz tones were used as stimuli. However, they reported quite accurate localization (no bias) when a higher-frequency tone (5 kHz) was used as a target. Bulter et al. (1967) found that localization judgments for tone bursts located at 50° or 70° from the midsaggital plane show a progressive shift toward 0° azimuth (medially) as the stimulus frequency shifted from 0.5 Hz to 2.4 kHz. They also reported a slight shift laterally (toward ±90°) as frequency increased to 4 kHz. If we consider that the target signal used in the present study is dominated by energy in the 0.5- to 0.75-kHz region and look at these frequencies in the Bulter et al. (1967) study only, the actual bias for 50° azimuth is only about 2.5° (figure 1, p. 173). It is important to note, however, that the authors pooled together the results for three SLs (15-, 25-, 35-dB SL) as well as for left and right locations because of no apparent influence of both these conditions on the obtained results. When they examined bands of noise (<1, 2–4, and >6 kHz) presented in quiet, only the 2- to 4-kHz responses were displaced medially (toward 0° azimuth). For frequencies <1 kHz, responses were minimally biased (0°–5°) for locations between 0° and 80° azimuth. Listeners in this study displaced intermediate frequencies (2–4 kHz) by as much as 40^o medially for tone bursts. Unlike Bulter et al. (1967), who can make statements about the bias for intermediate locations, we cannot make such clear statements because of our experimental design restrictions.

Medial and lateral biases are not the only two localization biases proposed in the literature. Good and Gilkey (1996) and Good et al. (1997) found that localization judgments had a tendency to be shifted toward the position of the noise source when the SNR was low. Other researchers have reported the presence of the same "pulling effect" toward the region of the noise source (Bulter and Naunton, 1964; Langendijk et al., 2001; Lorenzi et al., 1999). Conversely, Suzuki and Sone (1987), Kopco et al. (2001), and Lorenzi et al. (1999) found, for some listeners, a dominant “pushing effect” (i.e., localization responses reported away from the true target source) when the signal and noise were presented either simultaneously or sequentially. In the present study, responses at the location of the DN source (pulling effect) were observed for many target-noise conditions at the lowest sensation levels; this was especially true for S_oN_o, $S_{-90}N_{-90}$, and $S_{180}N_{180}$.

A reason for the differences in the localization biases observed across studies may have resulted from differences in specific target-noise configurations tested. Some studies examined localization responses to targets originating from only the frontal hemisphere. As a result, the extent of bias may be less because listeners had a limited response area from which to choose when recording a response. Another experimental design difference between studies that may account for differences in reported biases includes the use of visible loudspeaker locations and forced-choice responses; if errors are present, they can be artificially larger or smaller because of the limited number of loudspeaker locations. Additionally, differences in reported biases may result from the selection of target and noise types (e.g., speech, tones, and noise bands). Another reason for differences in reported biases (and localization performance in general) may be the method used to summarize the data (e.g., use of mean values vs. median values). Finally, when a limited number of target-noise configurations or listeners are used, the same results may be interpreted differently among researchers.

4. Conclusions

Accurately processed and interpreted binaural and monaural spatial cues enable a listener to localize target signals in the acoustic environment. However, when the environment becomes too noisy, reverberant, or cluttered with additional sounds, spatial hearing cues become impoverished, and a listener’s ability to resolve the acoustic environment deteriorates. Despite the important practical value of information about human localization ability in noise, unanswered questions remain about the combined effects of spatial separation between sources, signal-to-noise condition, and sound character on localization precision. The present study was intended to examine some of these issues.

The focus of the study was to examine a listener’s ability to locate the source of a speech signal in the presence of either directional or nondirectional noise. The speech target was presented at four sensation levels and separated from the noise source by varying amounts. The results of the present study indicated that localization performance decreased as audibility of the target signal decreased; however, the slope of degradation varied across S positions and depended on the signal location, noise location, and angular separation between the two. In addition, the results indicated that often a target could be heard clearly but not localized accurately. It appears from the data that when a target is clearly audible and originates from directly in front of (0°) or to the side of a listener (±90°), regardless of the amount of spatial separation between the target and noise source, localization performance is good. Specifically, stable and highly accurate localization judgments require a 12- to 18-dB SL when a target originates at 0° azimuth and about an 18-dB SL for a target originating at 90°. For almost all other target positions, localization performance did not reach a high level, even when the target signal was clearly audible (i.e., 18-dB SL). These results support the notion that signal-to-noise conditions required for accurate localization of a target from all positions in the environment may need to be higher than the levels tested in this experiment. However, it is possible that optimal localization of targets from all positions will never be achievable in noise, even at higher sensation levels, without the aid of training, feedback, and/or free head movement.

Finally, errors and directional biases in localization judgments were observed in the study across target-noise conditions and sensation levels. The fewest errors in localization judgments were left-right and right-left errors (1%–8% of all errors across sensation levels). FB and BF errors accounted for about 5%–15% and 15%–40% of errors, respectively, with BF errors dominating in this experiment. Directional biases in listener judgments of target source location were noted as well, with lateral biases (toward ±90°) occurring for targets at ±45° and ±135° azimuth and medial biases (toward 0°) occurring for targets originating from ±90° azimuth at all sensation levels. At the lowest sensation levels, a pulling effect of localization judgments toward the noise source was observed for some target-noise locations.

The results of this study highlight the importance of considering target signal detectability (audibility) in noise and its potential effect on sound localization performance. Future studies will compare localization performance in noise-free and noise-filled environments for targets presented at higher sensation levels to determine whether good localization performance in noise can be achieved at additional target locations and at performance levels comparable to levels found in quiet environments. The results of the current study and planned studies may assist in establishing localization norms for signals presented in noise-filled environments. Such information may be useful to designers of auditory displays for both commercial and military applications and to audiologists working in clinical settings. When target-noise conditions are standardized with normal-hearing listeners in real and/or simulated auditory environments, further standardization can be completed with hearing-impaired listeners. Standardizing localization performance may lead to the development of a clinical test that may help clinicians demonstrate to patients various changes in localization ability after listening training, being fitted with amplification devices, or middle-ear surgery (e.g., stapedectomy).

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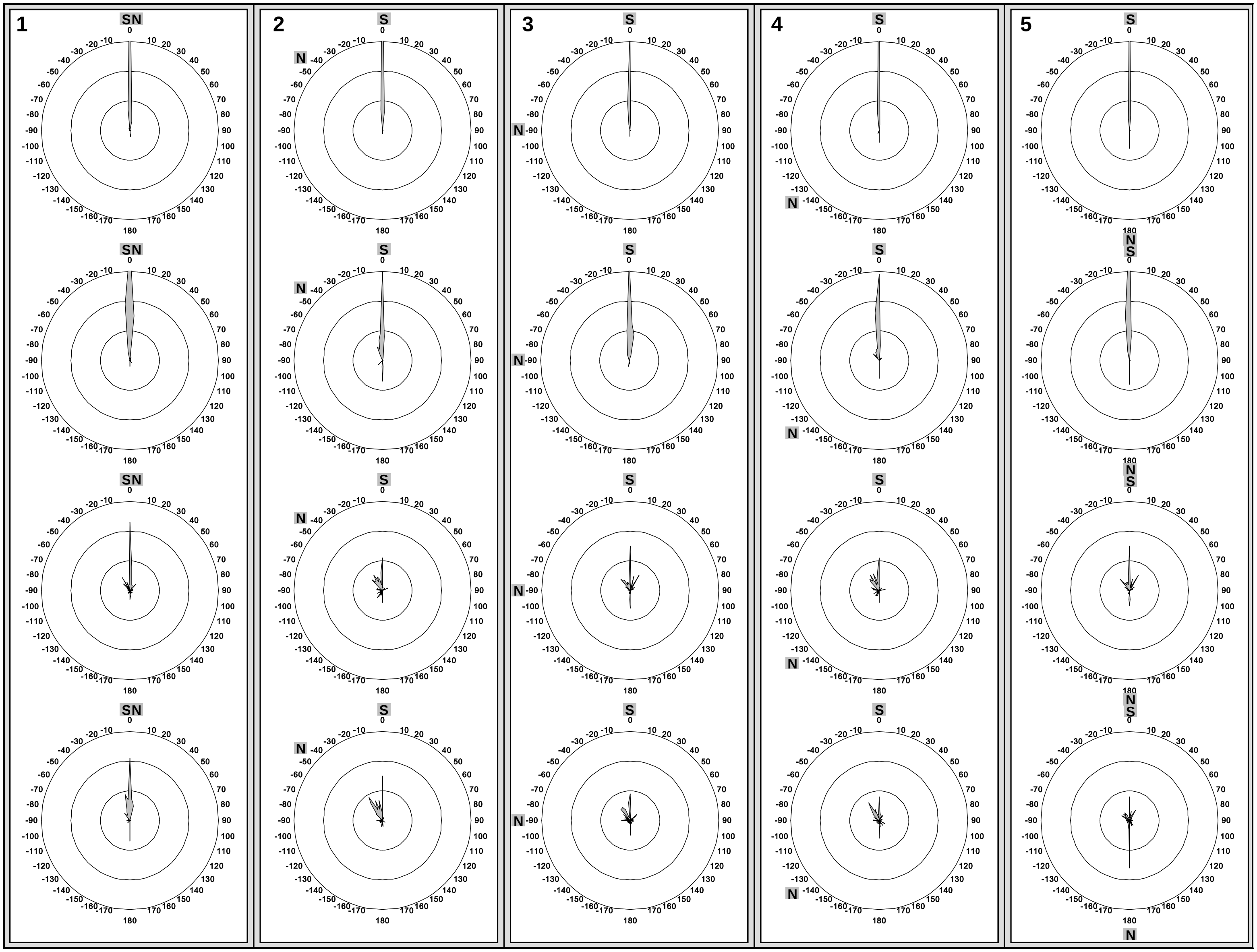
Appendix A. Polar Plots of Localization Responses

This appendix contains polar plots of localization responses obtained from listeners in the 40 target-noise conditions as a function of sensation level (SL). The number in the upper left-hand corner of a panel represents the target-noise condition. Each panel includes four polar plots showing the data for sensation levels of 0-, 6-, 12-, and 18-dB SL on the bottom, lower-mid, upper-mid, and top panel, respectively. S represents the location of the target signal, and N represents the location of the directional noise (DN) (panels 1–35). When nondirectional noise (NDN) was present (panels 36–40), only S is presented on the polar plots.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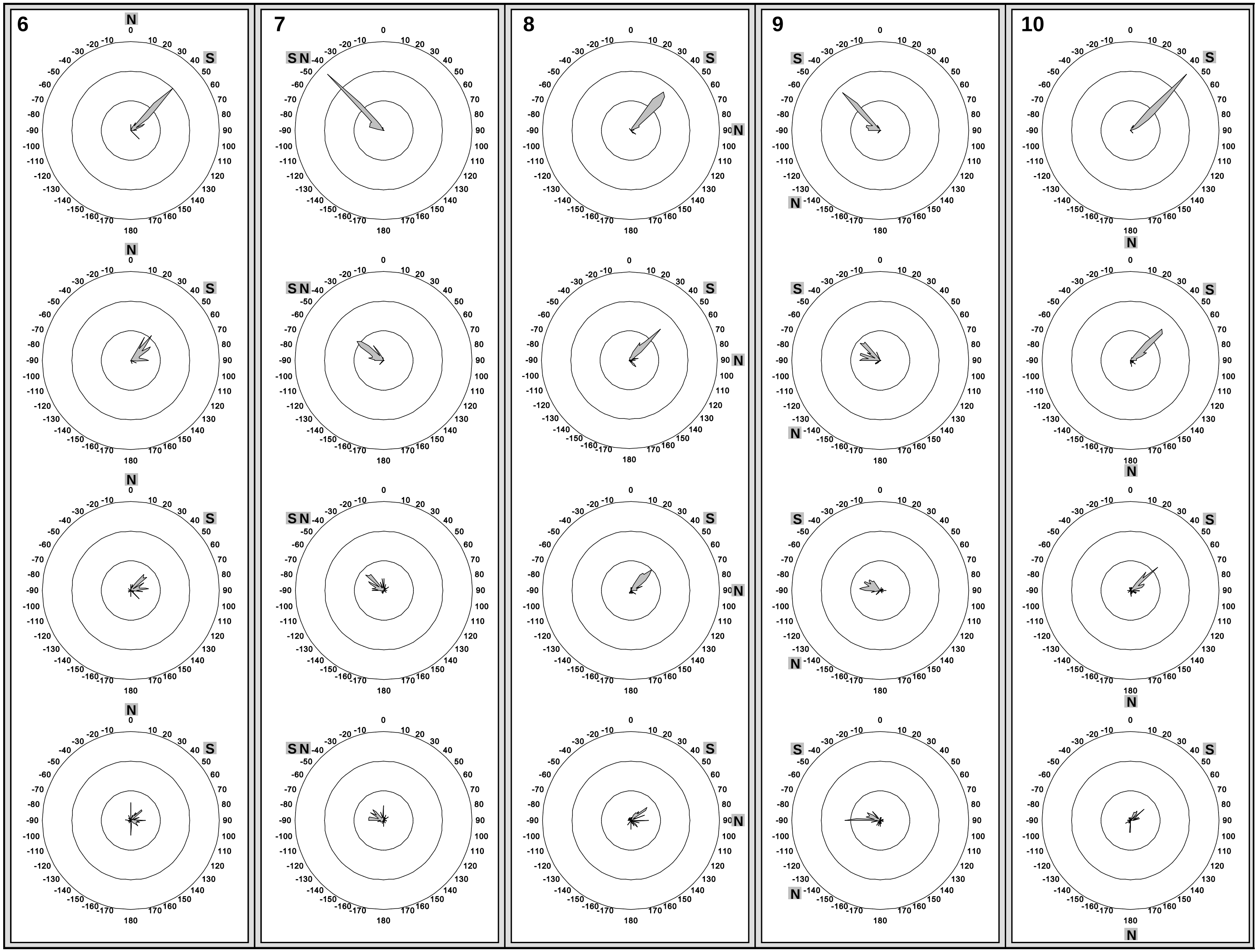
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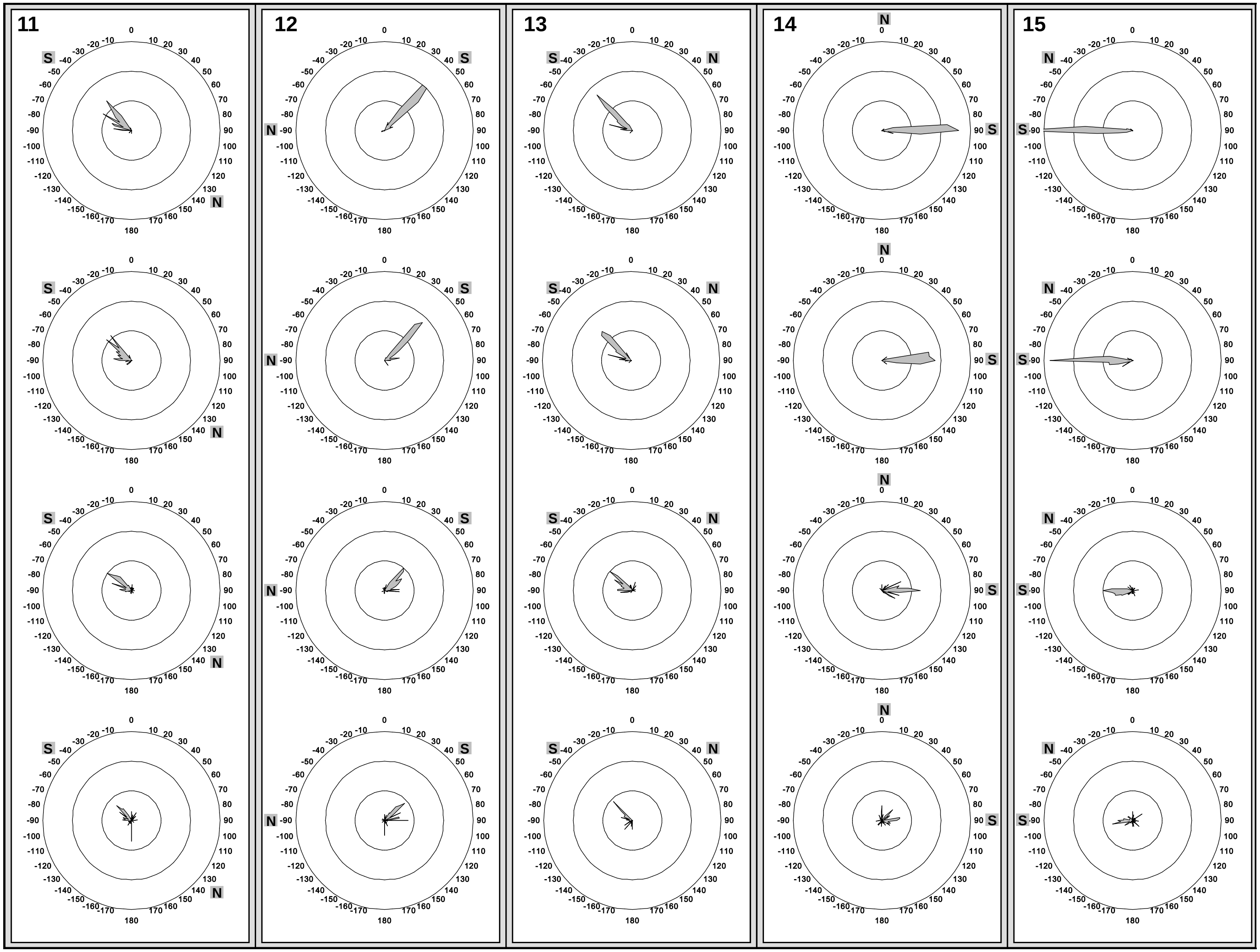
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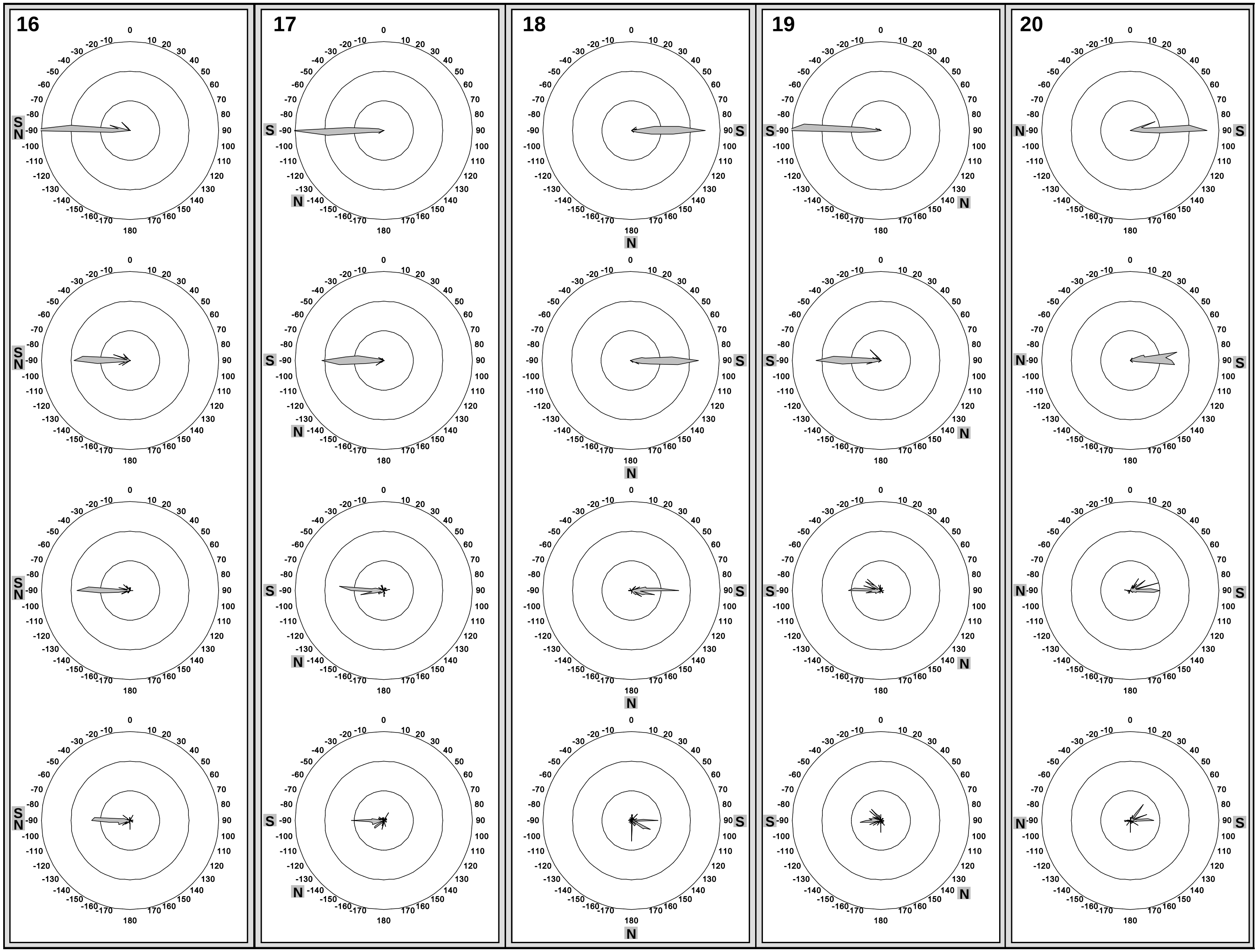
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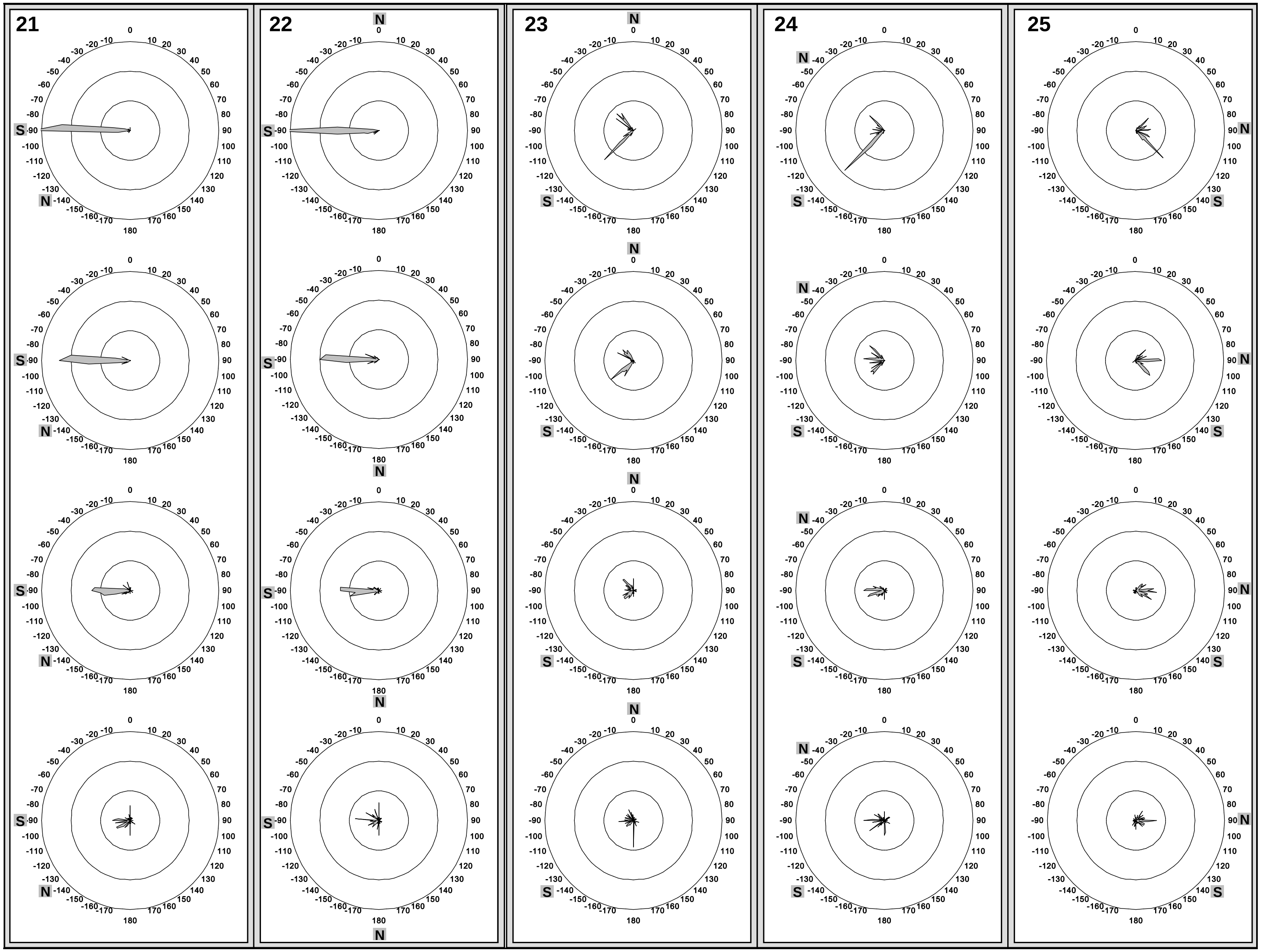
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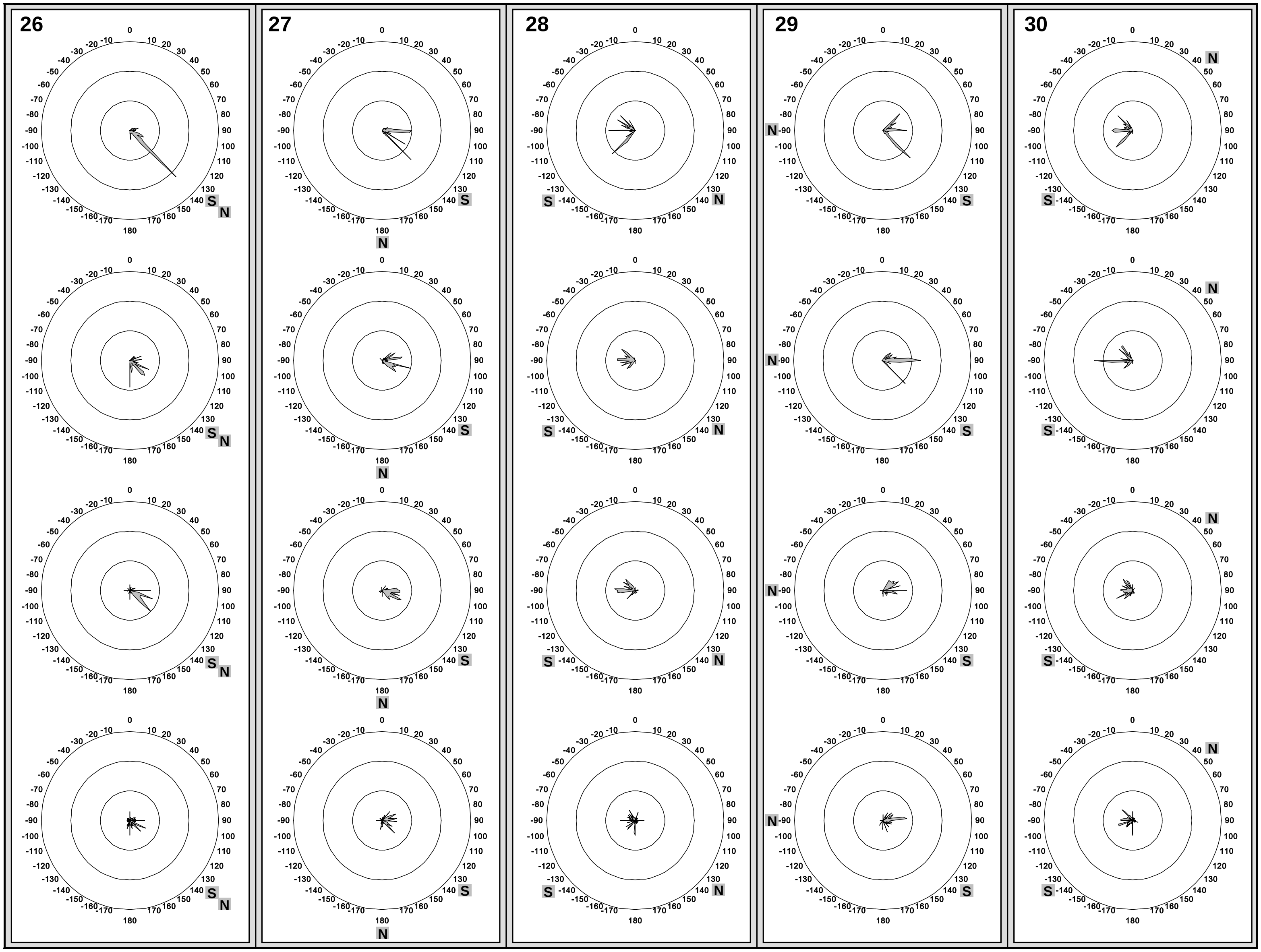
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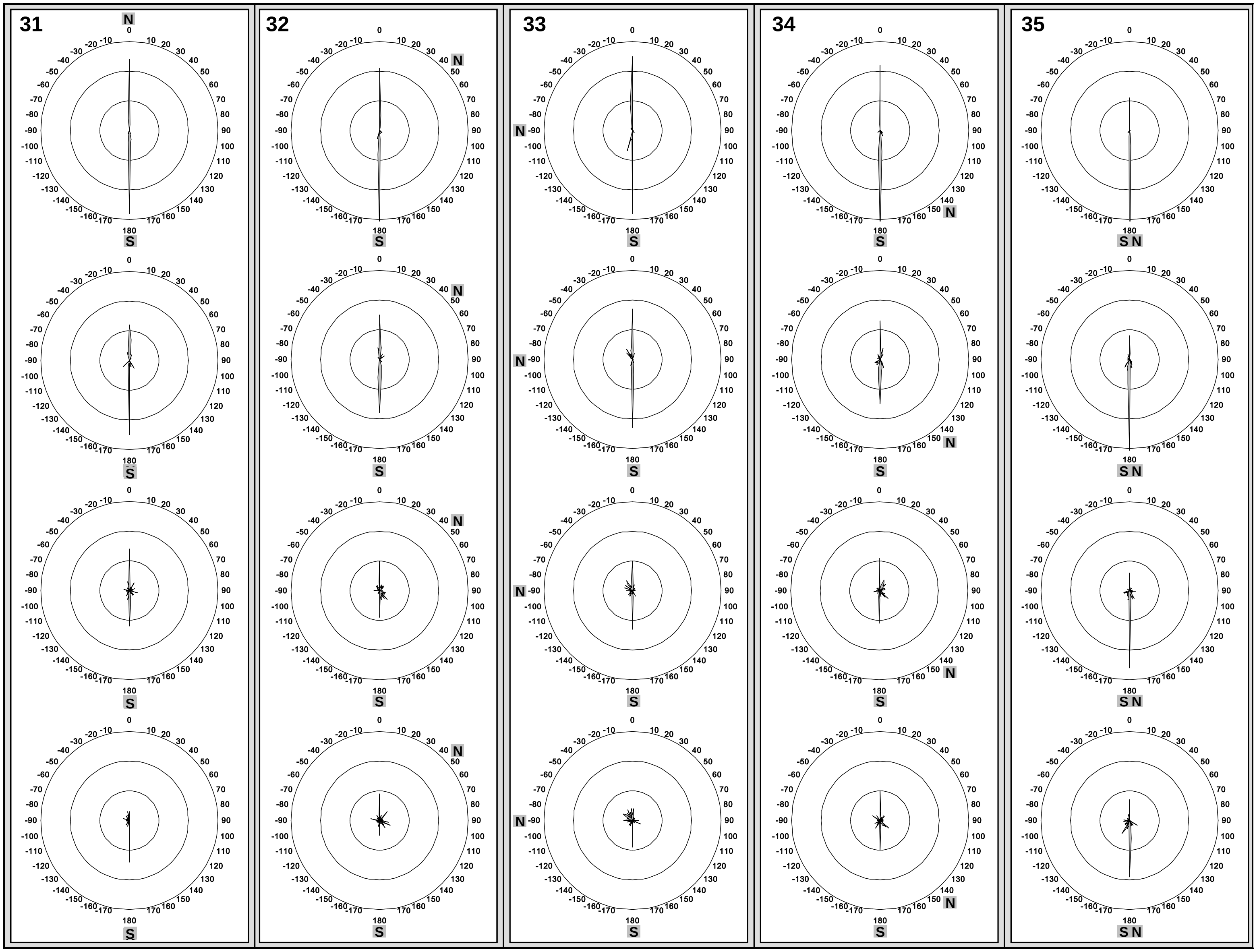
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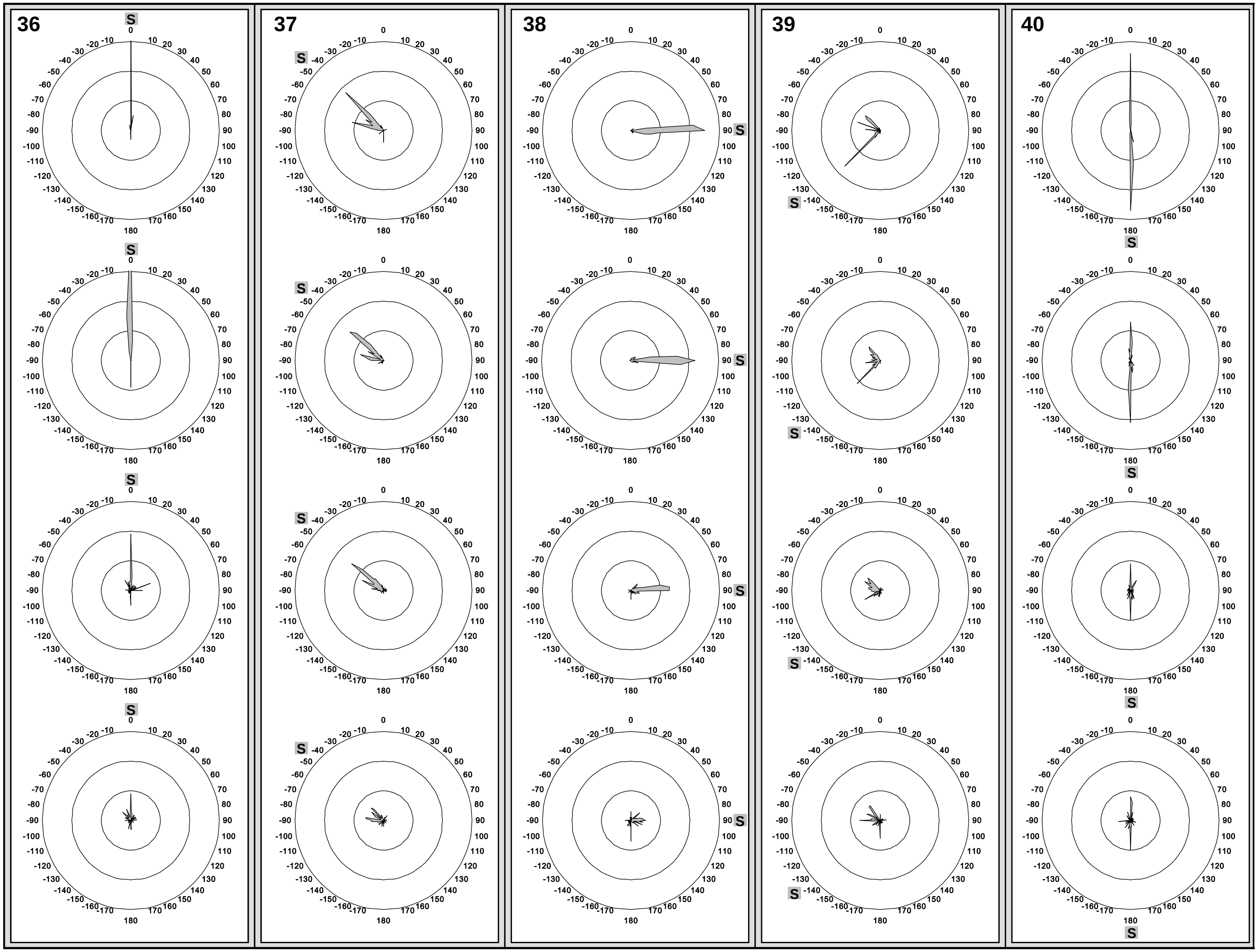
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Appendix B. Summary Statistics

This appendix shows the summary statistics for the 40 target-noise conditions as a function of sensation level (SL). Numbers 1–40, as listed in the first column, represent the target-noise condition. For each SL, the 25th quartile (Q_1), median (Med), 75th quartile (Q_3), interquartile range ($Q_1 – Q_3$), and signed LE_s are represented in degrees azimuth. For S_0 and S_{180} conditions, positive LE_s values represent an error toward the listener's left side, and negative LE_s values represent an error toward the listener's right side. Positive and negative values for $S_{\pm 45}$, $S_{\pm 90}$, and $S_{\pm 135}$ represent rearward errors and frontward errors, respectively. All table values are reported in degrees azimuth.

	Condition	18 dB SL Accuracy Q_1	Med	Q_3	IQR	Error LE_s	12 dB SL Accuracy Q_1	Med	Q_3	IQR	Error LE_s	6 dB SL Accuracy Q_1	Med	Q_3	IQR	Error LE_s	0 dB SL Accuracy Q_1	Med	Q_3	IQR	Error LE_s
1	S_0 N_0	-1.2	-0.1	0.8	2.0	-0.1	-3.6	-1.0	1.6	5.1	-1.0	-12.2	-0.1	30.9	43.0	-0.1	-12.2	-0.1	3.8	16.0	-0.1
2	S_0 N_{-45}	-1.9	-0.9	0.0	1.9	-0.9	-13.9	-1.7	1.8	15.6	-1.7	-20.0	0.7	16.8	36.7	0.7	-32.1	2.9	39.4	71.6	2.9
3	S_0 S_{-90}	-1.8	-0.3	0.5	2.3	-0.3	-1.3	1.6	5.2	6.5	1.6	-41.4	-23.1	-6.7	34.7	-23.1	-39.2	-6.2	5.6	44.8	-6.2
4	S_0 N_{-135}	-1.8	-1.0	0.1	2.0	-1.0	-14.0	-2.7	0.1	14.0	-2.7	-68.1	-29.4	-4.5	63.6	-29.4	-47.4	-23.1	2.1	49.5	-23.1
5	S_0 N_{180}	-1.5	-0.4	0.3	1.8	-0.4	-13.7	-1.7	1.7	15.4	-1.7	-34.0	-2.5	15.5	49.5	-2.5	-87.3	-10.8	28.5	115.8	-10.8
6	S_{45} S_0	42.4	47.3	61.3	19.0	2.3	40.4	54.8	77.2	36.9	9.8	39.7	57.3	84.6	44.9	12.3	22.6	61.0	109.1	86.5	16.0
7	S_{-45} N_{-45}	-60.2	-46.1	-42.8	17.4	1.1	-69.1	-56.3	-44.8	24.4	11.3	-70.9	-50.2	-26.1	44.8	5.15	-80.5	-53.9	-17.1	63.4	8.9
8	S_{45} N_{90}	37.7	44.5	50.2	12.5	-0.5	38.6	45.3	61.6	23.1	0.3	36.6	49.1	68.9	32.3	4.1	9.4	70.5	104.0	94.7	25.5
9	S_{-45} N_{-135}	-70.4	-49.4	-44.1	26.3	4.4	-83.3	-65.8	-46.9	36.4	20.8	-83.4	-65.8	-46.2	37.2	20.8	-90.0	-75.9	-51.8	38.3	30.9
10	S_{45} N_{180}	43.5	47.5	53.8	10.3	2.5	46.2	58.4	67.9	21.7	13.4	44.8	53.9	85.4	40.6	8.9	29.7	63.9	102.1	72.5	18.9
11	S_{-45} N_{135}	-71.0	-54.9	-42.3	28.7	9.9	-83.4	-59.0	-46.8	136.6	14.0	-70.9	-54.0	-39.0	31.9	9.0	-83.0	-47.1	-3.1	80.0	2.1
12	S_{45} N_{-90}	39.1	44.6	48.9	9.7	-0.4	42.0	47.90	63.1	21.1	2.9	40.2	54.3	69.8	29.6	9.3	37.6	51.2	78.5	40.9	6.2
13	S_{-45} N_{45}	-66.9	-50.0	-44.9	21.9	5.0	-84.1	-63.3	-47.9	36.2	18.3	-82.5	-58.4	-44.4	38.1	13.4	-86.4	-48.8	-31.1	55.3	3.8
14	S_{90} N_0	84.4	88.3	92.3	7.9	-1.7	81.7	88.3	93.3	11.6	-1.8	73.5	87.7	102.3	28.9	-2.3	0.2	69.2	95.8	95.6	-20.9
15	S_{-90} N_{-45}	-92.0	-89.1	-87.0	5.1	1.0	-94.6	-89.2	-86.2	8.4	-0.9	-105.1	-90.1	-71.6	33.5	0.1	-98.1	-57.2	55.7	153.8	32.9
16	S_{-90} N_{-90}	-90.4	-88.1	-83.7	6.8	-2.0	-93.1	-87.9	-79.8	13.4	-2.2	-93.2	-88.6	-76.7	16.5	-1.4	-102.3	-89.1	-71.7	30.6	-0.9
17	S_{-90} N_{-135}	-93.5	-90.3	-87.0	6.5	0.3	-93.7	-90.0	-83.9	9.9	0.0	-100.0	-86.3	-75.3	24.7	-3.8	-119.4	-91.5	-68.2	51.3	-1.5
18	S_{90} N_{180}	86.2	90.0	93.2	7.0	0.0	86.0	90.6	96.5	10.5	0.6	80.9	89.4	105.4	24.5	-0.7	44.7	103.8	125.0	80.3	-13.8
19	S_{-90} N_{135}	-91.1	-87.7	-84.5	6.7	-2.3	-92.9	-87.8	-82.5	10.4	-2.2	-90.4	-77.8	-44.9	45.5	-12.2	-101.0	-79.0	-35.6	65.4	-11.0
20	S_{90} N_{-90}	82.5	87.9	91.2	8.7	-2.1	79.0	84.6	91.8	12.8	-5.5	50.8	76.3	89.6	38.8	-13.7	35.7	65.3	89.0	53.3	-24.7
21	S_{-90} N_{135}	-89.6	-88.1	-84.9	4.8	-2.0	-95.3	-88.5	-86.0	9.3	-1.5	-100.2	-89.4	-82.0	18.2	-0.7	-121.5	-90.2	-10.9	110.6	-0.2
22	S_{-90} N_0	-95.6	-90.0	-88.0	7.7	0.0	-95.2	-88.3	-84.2	11.1	-.7	-98.2	-88.8	-74.6	23.6	-1.2	-115.0	-72.6	-7.0	108.0	-17.4
23	S_{-135} N_0	-135.0	-120.0	-46.0	89.0	-15.0	-136.7	-115.9	-47.5	89.2	-25.9	-126.1	-76.2	-36.2	89.9	-13.8	-114.1	-71.6	-10.7	103.5	-18.4
24	S_{-135} N_{-45}	-135.0	-117.0	-69.0	66.0	-18.0	-122.6	-86.8	-61.4	61.2	-48.3	-114.4	-88.5	-67.8	46.6	-46.5	-119.9	-77.0	-0.8	119.2	-58.1
25	S_{135} N_{90}	66.4	109.5	135.0	68.7	-25.6	160.4	90.0	128.9	-31.5	-45.0	48.9	87.9	113.2	64.3	-47.1	9.4	70.45	104.0	94.7	-64.6
26	S_{135} N_{135}	110.2	131.7	136.1	25.9	-3.4	100.4	129.5	152.4	52.0	-5.5	89.0	111.2	132.3	43.3	-23.9	-1.0	91.1	133.1	134.1	-44.0
27	S_{135} N_{180}	87.7	101.6	133.2	45.5	-33.5	76.03	105.1	121.7	45.6	-29.9	84.2	102.4	119.8	35.6	-32.7	39.7	80.4	119.2	79.5	-54.7
28	S_{-135} N_{135}	-134.3	-84.5	-59.4	74.9	-50.5	-111.8	-87.2	-61.2	50.6	-47.9	-97.4	-81.2	-49.4	48.1	-53.9	-126.9	-69.5	-23.4	103.5	-65.6
29	S_{135} N_{-90}	60.1	88.5	134.9	74.8	-46.5	74.6	88.3	107.9	33.3	-46.8	58.4	81.7	100.5	42.1	-53.4	42.6	79.9	102.6	60.0	-55.1
30	S_{-135} N_{45}	-128.0	-87.3	-54.1	73.9	-47.8	-104.5	-88.5	-50.2	54.4	-46.6	-116.2	-81.2	-42.8	73.4	-53.9	-119.3	-84.9	-39.2	80.1	-50.1
31	S_{180} N_0	-179.2	-1.1	2.2	181.4	-178.9	-170.4	0	29.3	199.7	180.0	-34.3	2.2	132.1	166.4	177.8	-145.8	-2.5	21.3	167.1	177.5
32	S_{180} N_{45}	-179.0	-2.6	1.8	180.8	-177.4	-22.2	2.2	58.7	80.8	2.2	-9.1	25.6	140.8	150.0	154.4	-48.5	19.5	114.1	162.6	160.5
33	S_{180} N_{-90}	-178.3	-3.1	1.0	179.3	-176.9	-176.0	-11.1	1.2	177.2	-169.0	-136.7	-33.1	-0.8	135.8	-146.9	-84.3	-33.7	5.9	90.3	-146.3
34	S_{180} N_{135}	-178.3	-1.2	143.7	322.0	-178.9	-166.1	-1.1	22.2	188.4	-179.0	-14.8	-28.2	122.6	137.4	-151.8	-80.8	-1.9	129.5	210.3	-178.1
35	S_{180} N_{180}	-180.0	-178.1	0.5	180.5	-1.9	-178.5	-124.8	164.4	342.8	-55.2	-174.9	-56.2	155.2	330.0	-123.9	-161.4	-97.1	137.2	298.6	-83.0
36	S_0 N_{NDN}	-1.7	-0.0	0.8	2.5	-0.0	-3.8	-0.1	1.65	5.5	-0.1	-25.5	0.4	179.4	204.9	0.4	-74.0	-3.5	37.9	111.9	-3.5
37	S_{-45} N_{NDN}	-73.1	-55.1	-45.0	28.1	10.0	-78.3	-55.1	-45.7	32.5	10.1	-67.5	-49.3	-41.5	26.0	4.3	-93.4	-67.2	-40.6	52.8	22.2
38	S_{90} N_{NDN}	85.4	89.1	96.1	10.7	-0.9	83.0	88.5	933.8	10.9	-1.5	74.8	86.8	93.4	18.6	-3.2	-88.5	63.1	93.3	181.8	-27.0
39	S_{-135} N_{NDN}	-134.0	-88.1	-56.0	78.0	47.0	-133.7	-100.3	-53.9	79.8	-34.8	-114.2	-75.2	-51.8	62.4	-59.9	-128.6	-85.4	-49.9	78.7	-49.7
40	S_{180} N_{NDN}	-175.1	0.2	166.6	341.8	180.0	-176.9	-1.3	18.9	195.8	-178.8	-136.0	-0.4	76.2	212.2	-179.6	-120.3	-2.1	42.6	162.9	-178.0

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